Holocene environmental change in Northwest Iceland

Sigrún Dögg Eddudóttir

Faculty of Life and Environmental Sciences
University of Iceland
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Dissertation submitted in partial fulfillment of a
Philosophiae Doctor degree in Geography

Advisors
Dr. Egill Erlendsson (University of Iceland)
Prof. Guðrún Gísladóttir (University of Iceland)

PhD Committee
Dr. Egill Erlendsson (University of Iceland)
Prof. Guðrún Gísladóttir (University of Iceland)
Dr. Ólafur Eggertsson (Icelandic Forest Service)

Opponents
Dr. Ian T. Lawson (University of St Andrews)
Prof. Ólafur Ingólfsson (University of Iceland)

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

Telephone: 525 4000

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Abstract

For most of the Holocene the main driver of vegetation and environmental change in Iceland was climate, although intermittent volcanic events had short term impacts. This changed with the Norse colonisation in the late 9th century AD, from when land use became a dominant force in terrestrial ecosystem development. This thesis presents a regional vegetation and environmental reconstruction from Northwest Iceland, based on data from three lake sediment cores and one peat core. The aim of the study was to examine the sensitivity of the Icelandic terrestrial ecosystem to external forcing mechanisms i.e. climate, tephra deposition and land use. The study sites form a transect from the coast on northern Skagi peninsula, through the lowland to the highland margin.

The reconstructions reveal that vegetation changes were asynchronous between sites as a result of their different environmental settings. Vegetation changes in the lowland were primarily driven by climate. Based on pollen data the warmest periods of the Holocene were *c*. 10,100-8700 and 8000-6000 cal. yr BP and the optimum period for *Betula pubescens* woodland was *c*. 8000-6000 cal. yr BP. Cooling climate led to a woodland decline after *c*. 6000 cal. yr BP.

Vegetation succession in the early Holocene was slower at the highland margin than in the lowland. Open woodland developed *c*. 7800 cal. yr BP and persisted until *c*. 4200 cal. yr BP. The woodland was probably at its ecological limit for most of that time. Human settlement began to influence the environment at the highland margin *c*. 1000 cal. yr BP, marked by changes in vegetation and increased environmental instability.

Birch woodland is not observed in the record from the coast, probably due to oceanic influences. Dwarf shrub heath probably endured there throughout the Holocene.

Examination of the influence of the Hekla 4 tephra (*c*. 4200 cal. yr BP) on vegetation revealed that the tephra had an impact on both relatively stable open woodland in the lowland and open woodland under pressure at the highland margin. The vegetation community at Barðalækjartjörn passed a tipping point at the time of the tephra fall and the struggling woodland was replaced by a hardier ecosystem, dwarf shrub heath.

Útdráttur

Umhverfi Íslands hefur tekið miklum breytingum frá landnámi. Fyrir landnám var loftslag helsti áhrifaþáttur gróður- og umhverfisbreytinga en einnig höfðu eldgos skammvinn áhrif. Til rannsóknar í þessari ritgerð eru eðli og ástæður gróður- og umhverfisbreytinga í Austur-Húnavatnssýslu á nútíma, bæði í tíma og rúmi. Saga umhverfisbreytinga er byggð á greiningum frjókorna, plöntuleifa og seteiginleika úr þremur stöðuvötnum og einum mýrarkjarna. Rannsóknastaðirnir mynda langsnið frá strandsvæði á Skaga upp að hálendisbrún.

Umhverfisaðstæður á hverjum stað höfðu mikil áhrif á gróðurframvindu og var töluverður munur á gróðurframvindu milli svæða. Gróðurfar á láglendi stjórnaðist að mestu af loftslagi. Hlýjustu skeið nútíma voru fyrir um 10.100-8700 og 8000-6000 árum. Birkiskógar náðu hámarksútbreiðslu fyrir um 8000-6000 árum en tók að hnigna vegna kólnandi loftslags fyrir um 6000 árum.

Gróðurframvinda á fyrri hluta nútíma var hægari við hálendisbrún þar sem birkikjarr eða skógur myndaðist fyrir um 7800 árum en birki var þar nálægt vistfræðilegum mörkum tegundarinnar. Birki hélt þar velli þar til fyrir um 4200 árum. Áhrif mannvistar verða greinileg fyrir um 1000 árum en þau koma fram í breytingum á gróðri og auknum óstöðugleika í umhverfinu.

Engin ummerki eru um birkikjarr eða skóga nyrst á Skaga, líklega vegna hafrænna áhrifa á vaxtarskilyrði birkis. Gróðurfar þar hefur líklega einkennst af lyngmóa allan nútíma.

Áhrif gjóskulagsins Heklu 4, sem féll fyrir um 4200 árum á gróður voru skoðuð sérstaklega. Gjóskufallið hafði áhrif bæði í stöðugu skóglendi á láglendi og opnu skóglendi/kjarri við hálendisbrún. Gjóskufallið ásamt kólnandi loftslagi gerði það að verkum að gróður við hálendisbrún breyttist varanlega úr birkikjarri eða skóglendi í fjalldrapamóa eftir gosið.

List of papers

Paper I. 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.

Paper II. Climate change and human impact in a sensitive ecosystem: the Holocene environment of the Northwest Icelandic highland margin. *Boreas, 45*(4), 715–728.

Paper III. Effects of the Hekla 4 tephra on vegetation in Northwest Iceland. Revised manuscript accepted for publication in *Vegetation History and Archaeobotany*.

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Abbreviations

cal. yr BP	Calibrated years before present (present assigned to AD 1950)
C/N	Carbon to nitrogen ratio
DBD:	Dry bulk density (g cm^{-3})
MS:	Magnetic susceptibility (SI)
OM:	Organic matter (%)
PAR:	Pollen accumulation rate (grains cm^{-2} $year^{-1}$)

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Firstly, I would like to thank my advisors Egill Erlendsson and Guðrún Gísladóttir for their guidance throughout my PhD studies. I consider myself very fortunate having had the two of them as my advisors. Their knowledge and suggestions have improved my work immensely and have helped me gain a better understanding of the complexities of environmental processes. Egill is blessed with an abundance of patience and throughout my PhD studies he has always been ready to discuss problems and opportunities that have come up along the way. He is off to a great start as a PhD advisor. Guðrún is a positive force for her students and is able to look at any problem from a very broad perspective and her insights have been invaluable throughout my studies.

I would like to thank the third member of my thesis committee, Ólafur Eggertsson, for his work in the field and identification of wood samples used for radiocarbon dating. I am grateful to reviewers and journal editors for their useful comments and suggestions on the papers.

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I have had the privilege to work alongside a lot of talented people during my studies. Guðrún's group and office 362 (now 358) have provided us with a place where we can always discuss our research, find a shoulder to cry on and discuss anything from our studies to life in general. On my first day in Askja I was greeted by Friðþór Sófus Sigurmundsson and Olga Kolbrún Vilmundardóttir who were rearranging the office that would be our second home for the next few years. From day one they have been my greatest allies in the PhD game and I will always be grateful for having met them. I would specially like to thank my role model Dr. OK for all the support and advice, especially during the past few months. I have had the privilege to share an office with some wonderful people throughout my studies, María Svavarsdóttir, Höskuldur Þorbjarnarson, Gyða Þórhallsdóttir, Theresa Bonatotzky, Scott John Riddell and Páll Kolka. I have also had the good fortune to spend a lot of my lab time with Utra Mankasingh and work on my project alongside Susanne Claudia Möckel and Leone Tinganelli. Thank you all for the banter, pranks, chocolate, gossip, gun talk, ninja action and all the good discussions on science and beyond. I would also like to thank Halldóra, Ríkey, Sigríður, Ingunn, Ágústa, Ágúst, Jón Bjarni, Jónas, Taru and other members of Askja past and present for their company through the years.

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1 Introduction

The late settlement of Iceland *c*. AD 870 allows scientists the unique opportunity to study an island‘s Holocene environmental history in a setting completely unaffected by human activities and herbivorous land mammals. Under these conditions the main driver of vegetation and environmental change is climate, with intermittent influences from volcanic events, mainly on short time scales (Caseldine et al., 2006; Eddudóttir et al., 2015; Eddudóttir et al., 2016; Hallsdóttir, 1995; Wastl et al., 2001). The well-known timing of Norse colonisation allows for an equally unique opportunity to research the impact of people on a previously pristine landscape. Frequent volcanic eruptions also contribute an important means of reconstructing past environments in Iceland. Abundant tephra layers buried in lakes and soils facilitate correlations between research sites and detailed tephrochronologies can aid in constructions of age models (e.g. Gudmundsdóttir et al., 2012; Óladóttir, 2009).

1.1 Holocene climate of Iceland

Lake sediments reveal relatively warm conditions during the Allerød interstadial (13,600-13,000 cal. yr BP) in Northwest Iceland (Rundgren, 1995). After a glacial advance during Younger Dryas (12,900-11,700 cal. yr BP), glaciers retreated rapidly (Larsen et al., 2012). Reconstructions from lowland sites in North Iceland, based on pollen and chironomid data, also depict relatively warm early Holocene conditions (Caseldine et al., 2006; Eddudóttir et al., 2015; Langdon et al., 2010). By *c*. 8700 cal. yr BP climate became cooler and more unstable (Geirsdóttir et al., 2013; Larsen et al., 2012). This cooling preceded a short, cold period recorded in marine sediments (Alley and Ágústsdóttir, 2005; Alley et al., 1997) and Greenland ice-core records (Thomas et al., 2007) *c*. 8200 cal. yr BP. Warm conditions resumed by *c*. 8000 cal. yr BP and lasted until *c*. 6000-5500 cal. yr BP (Caseldine et al., 2006; Eddudóttir et al., 2015; Geirsdóttir et al., 2013; Larsen et al., 2012; Striberger et al., 2012). This period is widely accepted as the warmest period of the Holocene, or the Holocene Thermal Maximum (HTM) in Iceland. Although few quantitative temperature reconstructions are available from Iceland, chironomid inferred July temperature (Ci-T) reconstructions from North Iceland have revealed warmer conditions than today between *c*. 10,500 and 8500 cal. yr BP (Langdon et al., 2010). This suggests that environmental development in North Iceland followed solar insolation during the early Holocene.

Cooling climate after *c*. 5500 cal. yr BP was followed by a shift towards increasingly unstable environmental conditions *c*. 4400-4200 cal. yr BP with the onset of Neoglaciation (Geirsdóttir et al., 2013; Larsen et al., 2012; Striberger et al., 2012). Relatively short cooling episodes have been proposed at *c*. 2900, 1400 and 700 cal. yr BP (Geirsdóttir et al., 2009; Larsen et al., 2012). It should be noted that increased environmental instability *c*. 4200 cal. yr BP coincides with a large eruption of the Hekla volcano in South Iceland which may have contributed to deteriorating environmental conditions along with cooling climate. The cooling trend was interrupted by a short warm period (Medieval Warm Period, MWP) between *c*. 1000 and 700 cal. yr BP, which was followed by intensified cooling at the beginning of the Little Ice Age (LIA) *c*. 700 cal. yr BP (Geirsdóttir et al., 2013; Larsen et al., 2011).

1.2 Holocene vegetation history of Iceland

Most paleoecological data for early Holocene vegetation development in Iceland are from North Iceland (Björck et al., 1992; Caseldine et al., 2006; Eddudóttir et al., 2015, 2016; Rundgren, 1995, 1998; Rundgren and Ingólfsson, 1999). The transition from fell-field vegetation of recently deglaciated landscapes towards *Juniperus communis* dominated communities between *c*. 10,100 and 9500 cal. yr BP occurred in response to early Holocene warmth (Eddudóttir et al., 2015; Hallsdóttir, 1995; Rundgren, 1998). The subsequent spread of birch (*Betula pubescens* Ehrh.) during the early Holocene is seen in pollen data from North and Northwest Iceland (Caseldine et al., 2006; Eddudóttir et al., 2015; Hallsdóttir, 1995). Woodland development was probably a result of increasingly stable environmental conditions as expanding vegetation cover trapped aeolian material and tephra left behind by retreating glaciers (Larsen et al., 2012; Striberger et al., 2012) and large eruptions of the Grímsvötn volcanic system (Jennings et al., 2014).

Birch woodlands of the mid Holocene are visible in pollen records from North Iceland (Caseldine et al., 2006; Eddudóttir et al., 2015; Hallsdóttir, 1995). The highest known tree lines of the Holocene date back to this period. Maximum birch distribution occurred between *c*. 7600 and 6800 cal. yr BP in Tröllaskagi peninsula (Wastl et al., 2001) and at the highland margin between 7800 and 6500 cal. yr BP (Eddudóttir et al., 2016). Woodlands declined after *c*. 6700 cal. yr BP and heaths and mires replaced previously wooded areas (Caseldine et al., 2006; Eddudóttir et al., 2015, 2016; Hallsdóttir, 1995; Hallsdóttir and Caseldine, 2005). Several episodes of birch woodland expansion during Neoglaciation have been identified, probably in response to short periods of ameliorating climate (Erlendsson and Edwards, 2009; Hallsdóttir, 1995).

Human settlement had great consequences for Icelandic vegetation and environment. Settlers began clearing woodland for haymaking and pastures, as well as for wood for fuel and building material (Dugmore et al., 2005; Hallsdóttir, 1987; Vickers et al., 2011). Human disturbance of ecosystems led to accelerated soil erosion as resilient woodland habitats were replaced by grassland and heath (Dugmore et al., 2005, 2009; Gathorne-Hardy et al., 2009; Gísladóttir et al., 2011; McGovern et al., 2007; Vickers et al., 2011). The cumulative effects of cooling climate within the last few millennia, frequent volcanic eruptions (Larsen and Eiriksson, 2008; Thordarson and Larsen, 2007) and the added stress of human settlement have shaped a modern environment that is vastly different from the woodlands of the mid Holocene (Caseldine et al., 2006; Eddudóttir et al., 2015; Hallsdóttir, 1995; Hallsdóttir and Caseldine, 2005). The extensive erosion of sensitive volcanic soils that began shortly after settlement remains a problem today (Arnalds, 2015; Arnalds et al., 2001, 2016).

The effects of tephra fall from volcanic eruptions on vegetation and ecosystems in Iceland are poorly understood. Great tephra falls from explosive eruptions have influenced the environment and people's livelihood since humans first settled Iceland *c*. AD 870. Eruptions such as the AD 1104 eruption of Hekla (Hekla 1104) (Larsen and Thorarinsson, 1977) and the Öræfajökull eruption in Southeast Iceland in AD 1362 are believed to have caused permanent abandonment of farms (Thorarinsson, 1958). Two of the largest explosive eruptions of the Holocene originate from the Hekla volcanic system. The Hekla 3 (*c*. 3000 cal. yr BP; Dugmore et al., 1995) and Hekla 4 (*c*. 4200 cal. yr BP; Dugmore et al., 1995) are estimated to have produced 12 km^3 and 9 km^3 of freshly fallen tephra, respectively (Larsen and Thorarinsson, 1977). These large eruptions probably had extensive effects on ecosystems in Iceland.

1.3 Aims of the research

The principal aim of the PhD project is to reconstruct the development of vegetation in Austur-Húnavatnsýsla, Northwest Iceland, during the Holocene, utilising paleoecological methods. Such an approach provides a suite of multi-proxy data that allows environmental context and change (e.g. climate, land use and volcanism) to be discerned.

The specific aims of the study were:

1. To examine the relationship between climate and Holocene vegetation and other environmental influences e.g. tephra fall in the lowland (**Paper I**).
2. To reconstruct Holocene vegetation changes at the highland margin, especially the development of birch woodland in response to changing climate (**Paper II**).
3. To examine whether birch woodlands were able to thrive in an oceanic climate on northern Skagi peninsula (Chapters 2, 3 and 4).
4. To examine the effects of the Hekla 4 tephra (4200 cal. yr BP) on two vegetation communities (**Paper III**).

Well resolved Icelandic pollen records which span a greater part of Holocene are rare (Caseldine et al., 2003; Hallsdóttir, 1995; Karlsdóttir, 2014; Vasari and Vasari, 1990; Wastl et al., 2001) and many of the available studies only cover short periods within the Holocene. A large body of work exists dealing with environmental changes around the time of human settlement (Erlendsson, 2007; Erlendsson and Edwards, 2009; Erlendsson et al., 2009; Gathorne-Hardy et al., 2009; Gísladóttir et al., 2010; Hallsdóttir, 1982, 1987; Lawson et al., 2007; Vickers et al., 2011) and a few studies have examined the vegetation and environment of the early Holocene (Caseldine et al., 2006; Rundgren, 1995, 1998; Rundgren and Ingólfsson, 1999). These studies are almost exclusively from lowland sites, with two exceptions (Hallsdóttir, 1982; Wastl et al., 2001) and therefore the central highlands are largely uncharted territory. This study includes the first complete Holocene vegetation reconstruction from the central highlands. Furthermore, it examines environmental development along a gradient from the coast, through lowland, up to the highland margin and offers one of the most comprehensive examination of Holocene environmental change in Iceland to date.

2 Methods

2.1 Study sites

The study sites are located in Austur-Húnavatnssýsla, Northwest Iceland (Figure 2.1). Kagaðarhóll (**Papers I & III**; Figure 2.1) is located ~10 km southeast of Húnaflói bay. The site is a 4.5 ha paleolake that now supports a bog vegetation community (Icelandic: *mýrar*). *Betula nana* dominated dwarf-shrub heath, eroded gravelly hills and semi-improved grassland surround the bog. Weather observations are available from a weather station, Blönduós, about 10 km northwest of Kagaðarhóll (Figure 2.1; Table 2.1).

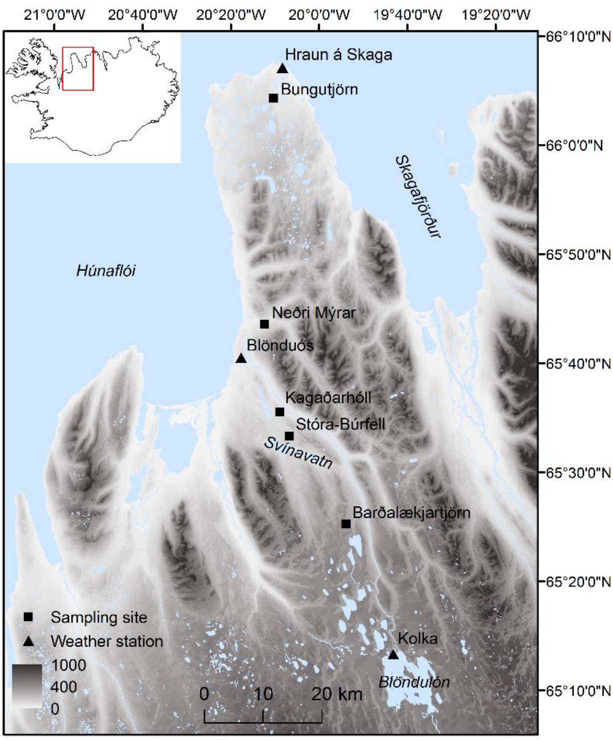

Figure 2.1 Location of sampling sites and weather stations mentioned in the text.

Barðalækjartjörn (**Papers II & III**; Figure 2.1), is situated on the margins of Auðkúluheiði heath, on the northern fringe of the central highlands. The lake is about 10 ha in area. *Carex* dominated wetland comprises the lake margin. The surrounding slopes are either dominated by hummocky dwarf shrub heath of *Betula nana*, *Calluna vulgaris* and *Salix* spp. or exposed, barren gravels. The closest weather station is Kolka, located at the northern end of the Blöndulón reservoir (Figure 2.1; Table 2.1) about 20 km south of Barðalækjartjörn.

Stóra-Búrfell (Figure 2.1; 65° 33.393'N, 20° 4.931'W, 140 m a.s.l.) is a drained wetland, about 4 km south of the Kagaðarhóll coring site. The former wetland is now utilised as hayfields. The closest weather station is located at Blönduós (Figure 2.1; Table 2.1).

Bungutjörn (Figure 2.1; 66° 4.030'N, 20° 10.074'W, 100 m a.s.l) is located on northern Skagi peninsula. The lake is about 7.4 ha in area. The lake is surrounded by eroded and sparsely vegetated glacier deposits. The closest weather station, Hraun á Skaga, is located about 6 km north of Bungutjörn (Figure 2.1; Table 2.1).

Table 2.1 Meteorological information from weather stations close to the study sites.

	Bungutjörn	***Kagaðarhóll/ Stóra-Búrfell***	***Barðalækjartjörn***
Closest weather station	Hraun á Skaga	Blönduós	Kolka
Period	1981-2011	1982-2013	1994 - 2014
Elevation	3 m a.s.l.	8 m a.s.l.	505 m a.s.l.
Mean tritherm temperature	~8.3°C	~9.3°C	~7.8 °C
Mean July temperature	~8.8°C	~9.9°C	~8.8 °C
Mean January temperature	~-0.8°C	~-1.4°C	~-4.4°C**
Mean annual precipitation	~543 mm	~456 mm*	~398 mm***

Unpublished data from the Icelandic Met Office.
*Mean rainfall 1982-2003.
**Data missing for 1994, 1996 and 2010.
***Data missing for 2003, 2004, 2008, 2010 and 2011.

2.2 Field methods and lithostratigraphy

The lake sediment cores were retrieved using a Livingstone piston corer and a Bolivia adaptor fitted with 75 mm diameter polycarbonate tubes. The peat core was retrieved from a soil section in a drainage ditch in the hayfields of the farm Stóra-Búrfell. The lake sediment cores were X-rayed before tubes were split in two halves. Magnetic susceptibility (MS) was measured at contiguous 1 cm intervals with a Bartington MS2 meter and Bartington MS2F probe (Dearing, 1994). Organic matter (OM, measured by loss on ignition) and dry bulk density (DBD; g cm^{-3}) were measured at contiguous 1 cm intervals. OM was measured by combusting 1.2 cm^3 of sediment at 550 °C for 5 hours (Bengtsson and Enell, 1986). DBD was calculated by dividing the dry weight of a sample by the volume of the undisturbed sample (Brady and Weil, 1996).

2.3 Laboratory methods

2.3.1 Dense-media separation

The traditional method of pollen extraction from sediments includes using hydrofluoric acid (HF) to dissolve siliceous materials (Faegri et al., 1989). A powerful corrosive chemical, HF is poisonous to humans if it comes into contact with skin or eyes, is ingested or inhaled (Kirkpatrick et al., 1995). Although widely used, the HF method is not robust enough to extract a sufficient amount of pollen from highly minerogenic sediments (Björck et al., 1978). Dense-media separation is an alternative to HF that is effective for extracting pollen grains from both minerogenic (Björck et al., 1978) and highly organic sediments (Nakagawa et al., 1998).

Preparation of pollen samples for this study using the traditional HF method (Faegri et al., 1989) yielded samples in which pollen grains were sparse, and were difficult and time consuming to count. Therefore a protocol for dense-media separation for the preparation of pollen samples was adapted from Björck et al. (1978) and Nakagawa et al. (1998). LST Fastfloat (a sodium heteropolytungstate solution) with a density of 1.9 g cm^{-3} is used in the new protocol. Pollen grains float in the higher density liquid while other particles such as tephra, clay and organic detritus sink.

To test the effectiveness and reliablility of the new method, eight sediment samples were mixed and sub-sampled for preparation with both the traditional HF method and the dense-media separation method. Initial tests of the dense-media separation method using a standard size sample of 1 cm^3 of lake sediments yielded very little material and therefore the standard size of sub-samples was increased to 2 cm^3. The dense-media separation method resulted in much cleaner samples than samples prepared using the traditional method. Percentages and concentrations of pollen grains were comparable between the two methods (Figure 2.2). The results also compare favourably with other studies comparing the two methods (Björck et al., 1978; Campbell et al., 2016; Nakagawa et al., 1998). The dense-media separation method therefore provides a safe and effective alternative to the HF method. The result is cleaner samples, leading to quicker counting of pollen slides. This increases the number of pollen samples that can be analysed, improving temporal resolution of pollen data. The dense-media separation method was used in the preparation of all pollen samples in this study.

2.3.2 Pollen and plant macrofossil analyses

Subsamples of 2 cm^3 were collected for pollen analysis (**Papers I, II & III**). Samples were prepared using standard chemical methods aside from HF (Faegri et al., 1989; Moore et al., 1991) and dense-media separation (Björck et al., 1978; Nakagawa et al., 1998). A minimum of 300 indigenous terrestrial pollen grains were counted for each sample, except for the three lowermost samples in the Kagaðarhóll core, where pollen concentrations were low. Pollen grains and spores were identified according to Moore et al. (1991) and a pollen type slide collection at the University of Iceland. Pollen categories and sums follow Hallsdóttir (1987) and Caseldine et al. (2006). Pollen and spore taxonomy follows Bennett (2016), with a few amendments to better reflect the Icelandic flora (Erlendsson, 2007). Pollen diagrams were constructed using TILIA (version 1.7.16) and pollen zones (PZs), based on terrestrial pollen assemblages, were calculated in in the TILIA program (Grimm, 2011) using CONISS (stratigraphically constrained cluster analysis by incremental sum of squares).

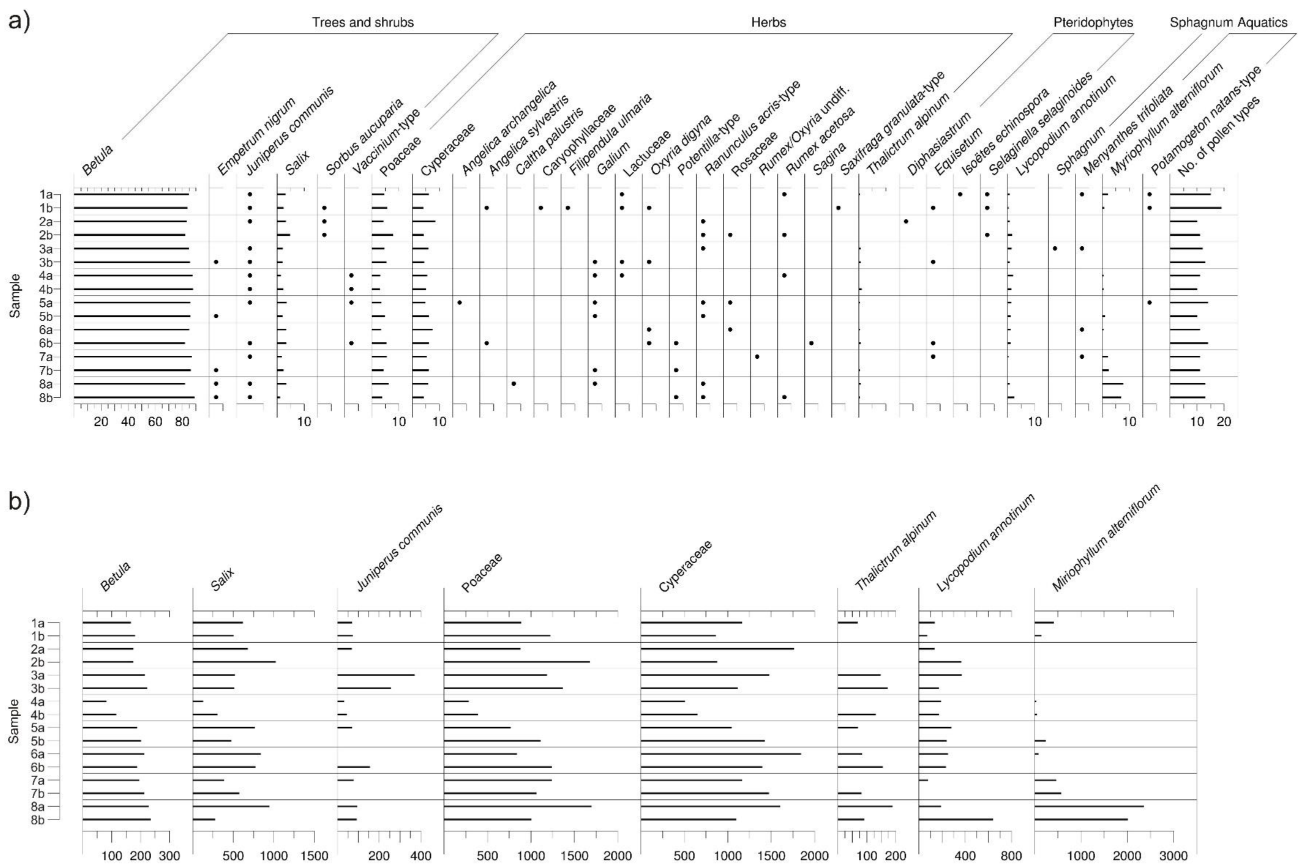

Figure 2.2 Comparison of pollen samples prepared using dense-media separation and hydrofluoric acid. Showing a pollen percentage and b) pollen concentrations. Samples prepared using dense-media separation are labelled 1a to 8a and samples prepared using HF are labelled 1b to 8b.

Principal Component Analysis (PCA) was performed on the dataset from Barðalækjartjörn (**Paper II**) and the datasets around the Hekla 4 tephra from Kagaðarhóll and Barðalækjartjörn (**Paper III**). The PCA analysis was performed on Hellinger transformed data consisting of terrestrial pollen taxa with percentages >1 %. Ordination was performed using the R package vegan (Oksanen et al., 2016).

Plant macrofossil samples were analysed at 5 cm contiguous intervals in the Kagaðarhóll and Barðalækjartjörn cores (**Paper I & II**). The Bungutjörn core was sampled at contiguous 5 cm. In the Stóra-Búrfell core 1 cm thick slices were cut every 5 cm. Sample volume varied between 25 and 55 ml and the volume of each sample was determined by displacement in water. Samples were washed through a 125 µm sieve and vascular plant remains were picked out for identification. Identification was based upon a range of literature (e.g. Berggren, 1969; Birks, 2007; Cappers et al., 2012; Katz et al., 1965) and comparisons with reference material. Concentrations of plant macrofossils in 50 ml were calculated. Macrofossil diagrams were constructed using the TILIA program (version 1.7.16; Grimm, 2011). Plant taxonomy follows Kristinsson (2010).

2.4 Tephra analysis

Tephra layers in all cores were identified visually and from changes in MS, DBD and OM. In addition, X-ray images were used for the lake cores. All tephra samples were washed through a 90 µm mesh sieve. Samples with mainly pristine volcanic glass shards were mounted on slides, polished and carbon coated before analysis. Major element analyses were performed using JEOL JXA-8230 electron probe microanalyser (EPMA) at the University of Iceland. Analyses of volcanic glass for the Kagaðarhóll core were also performed using a Hitachi TM3000 SEM equipped with a Bruker X-Flash silicon drift detector using 15 kV beam voltage applied to a surface of 10 × 10 µm.

2.5 Radiocarbon dating

Only three of the nine macrofossil samples from the Kagaðarhóll core initially sent for radiocarbon dating contained enough material for dating. Therefore six additional samples of aquatic plant remains and moss stems were radiocarbon dated (**Paper I**). For the Barðalækjartjörn core, eight samples of macrofossils were sent for radiocarbon dating (**Paper II**). As few plant macrofossils were found in the Bungutjörn core three bulk sediment samples from the lowest part of the core were used for radiocarbon dating (Table 2.2). Two wood samples from the Stóra-Búrfell peat core were used to date a dark-coloured Katla layer (S) (Table 2.2; **Paper I**) and two additional wood samples from the core were sent for dating (Table 2.2). Radiocarbon dates were calibrated to years before present (cal. yr BP) using IntCal13 (Reimer et al., 2013).

For the radiocarbon dating of lake sediments, aquatic plant macrofossils were preferred over bulk sediments, as radiocarbon dates of bulk material from Icelandic lakes are prone to errors and often do not correlate well with dated tephra layers (Caseldine et al., 2006). The dates from the bulk samples from the Bungutjörn sediments were not in chronological order (Table 2.2). Two samples above the 10,300 cal. yr BP Saksunarvatn tephra (194-218 cm depth) yielded ages that were older than the tephra (Table 2.2). The age increased upwards in the core, with an age of 10,903 ± 183 cal. yr BP at 187 cm depth and 11,166 ± 66 cal. yr BP at 180 cm depth.

Erosion-derived soil organic carbon is a known problem in Icelandic sediments after human settlement (cf. Gathorne-Hardy et al., 2009). Extensive soil erosion since the settlement has increased movement of old organic material/carbon that is inevitably deposited in lakes. This perhaps explains a discrepancy between the tephra-based chronology and a post-settlement radiocarbon date from a terrestrial plant macrofossil from the Barðalækjartjörn core (**Paper II**). One pre-settlement plant macrofossil sample from the Barðalækjartjörn also deviated from the regional tephrochronology based on major marker tephras in North Iceland (Eiríksson et al., 2000; Gudmundsdóttir et al., 2011a, 2011b, 2012; Larsen and Thorarinsson, 1977; **Paper II**). Even before the escalation of soil erosion following human settlement a reservoir effect perhaps existed in Icelandic lakes. A potential source of reservoir effect in Iceland apart from old organic material is geothermal activity. For example, geothermal activity creates a spatially variable, large reservoir effect in Lake Mývatn in Northeast Iceland (e.g. Ascough et al., 2007). However, the study sites in Austur-Húnavatnssýsla are not in the vicinity of known geothermal areas. Pre-settlement soil erosion may therefore explain the old date from Barðalækjartjörn as well as the post-Saksunarvatn dates from Bungutjörn.

A previous paleoecological reconstruction from Kagaðarhóll (see **Paper I**; Vasari, 1972, 1973; Vasari and Vasari, 1990) demonstrates the ambiguity of using radiocarbon dates from bulk sediments. Problems with the radiocarbon chronology of this reconstruction caused the misconception that *Betula pubescens* woodlands developed later in Austur-Húnavatnssýsla compared with other locations such as Skagafjörður and Eyjafjörður in North Iceland (Caseldine et al., 2006; Hallsdóttir, 1995). **Paper I** refutes this conception.

Table 2.2 Radiocarbon dated samples from the Bungutjörn core and Stóra-Búrfell peat section.

Sample	*Depth (cm)*	*^{14}C date (yr BP)*	*Error 1σ*	*$\delta^{13}C$ (‰)*	*Calibrated age 2σ error*	*Weight (mg)*	**Material**
Bungutjörn							
ETH-66140	180	9727	33	-13.1	11,231-11,100	0.65	Bulk sediment
ETH-66141	187	9552	36	-15.5	11,085-10,720	0.99	Bulk sediment
ETH-66142	226	9579	34	-13.2	11,100-10,750	1	Bulk sediment
Stóra-Búrfell							
SUERC-47865	67	6104	30	-29.2	7156-6888	2.5	Wood, *Betula* sp.
SUERC-47869	142	7988	30	-25.0*	8998-8725	2.5	Wood, unspecified

***Assumed**

2.6 Core chronologies

Age-depth models for the Kagaðarhóll (**Paper I**) and Barðalækjartjörn (**Paper II**) cores were constructed on the basis of tephra layers and radiocarbon dated plant macrofossils. A smoothed spline age-depth model for the Stóra-Búrfell core (Figure 2.3) was constructed using the Hekla 4 (4200 cal. yr BP; Dugmore et al., 1995), HUN (5530 cal. yr BP; Eddudóttir et al., 2016), Hekla Ö (6060 cal. yr BP; Gudmundsdóttir et al., 2011b) and Katla S (6600 cal. yr BP; Eddudóttir et al., 2015) tephra layers and two radiocarbon dates (Table 2.2). A linear age-depth model for the Bungutjörn core (Figure 2.3) was constructed using the Hekla 3 (3000 cal. yr BP; Dugmore et al., 1995), Hekla 4 (Dugmore et al., 1995), Katla S (Eddudóttir et al., 2015) and Saksunarvatn (10,300 cal. yr BP; Rasmussen et al., 2006) tephra layers. All age-depth models were constructed using the R package Clam (Blaauw, 2010). Ages are given in calibrated years before present (with present assigned to AD 1950).

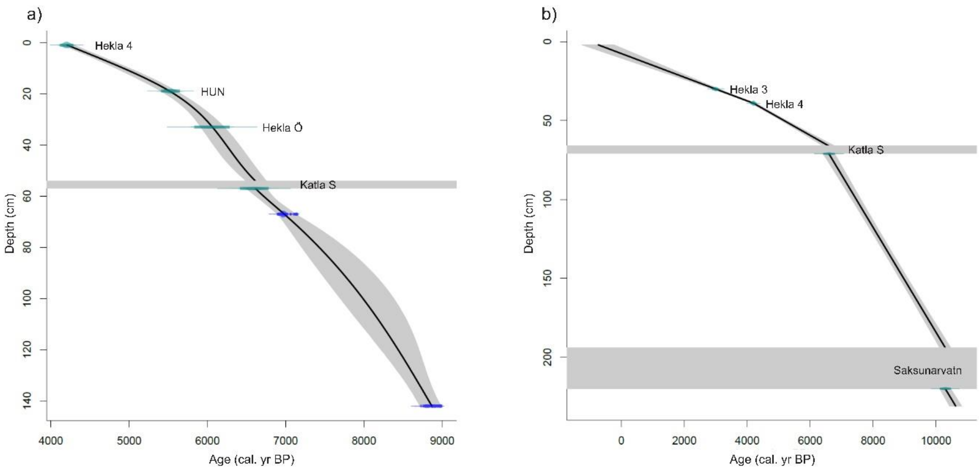

Figure 2.3 Age-depth models for a) the Stóra-Búrfell peat core and b) the Bungutjörn sediment core. Green symbols represent previously dated tephra layers and blue symbols indicate radiocarbon dates. The black line shows the best fit of the models, the grey area represents the 95 % confidence interval. Horizontal grey lines show tephra layers 2 cm or thicker.

3 Results

3.1 Kagaðarhóll (Paper I)

The pollen assemblage at Kagaðarhóll from *c*. 11,000 cal. yr BP is characterised by relatively high abundance of Poaceae and pioneer taxa such as *Oxyria digyna* and *Arenaria*-type. The total pollen accumulation rate (PAR) is very low (<100 grains cm^{-2} yr^{-1}) in the earliest part of the record. After *c*. 10,800 cal. yr BP *Empetrum nigrum* pollen peaks, and Cyperaceae and *Salix* pollen increase from *c*. 10,600 cal. yr BP. MS and DBD are high in the earliest part of the record but decrease after *c*. 10,600 cal. yr BP. The DBD decreases from ~0.45 to 0.20 g cm^{-3} and the OM increases from ~9 % to 24 %. The Saksunarvatn tephra, *c*. 10,300 cal. yr BP (Rasmussen et al., 2006) is marked by ~0 % OM and a steep increase in MS and DBD. Minerogenic inputs decline again above the tephra layer and recover to previous levels *c*. 100 years after the tephra was deposited, as seen from decreasing MS and DBD. *Juniperus communis* pollen appear by *c*. 10,200 cal. yr BP and increase to >30 % and >700 grains cm^{-2} yr^{-1} by 10,100 cal. yr BP. A peak in *Juniperus communis* PAR of 1000-3000 grains cm^{-2} yr^{-1} is recorded between *c*. 9800 and 9200 cal. yr BP. *Betula* PAR increases to a peak of >1000 grains cm^{-2} yr^{-1} between *c*. 9600 and 9400 cal. yr BP. *Betula pubescens* catkin scales and fruits are recorded continuously from *c*. 9300 cal. yr BP. Total terrestrial PAR reaches its highest levels in the core between *c*. 9500 and 9300 cal. yr BP, with values of ~4500–6100 grains cm^{-2} yr^{-1}, mainly due to an increase in *Juniperus communis* pollen. The total PAR decreases after *c*. 9200 cal. yr BP mainly due to a drop in the *Juniperus communis* PAR. After *c*. 8700 cal. yr BP *Betula* percentages decrease to ~25–30 %, the *Betula* PAR drops to ~160-260 grains cm^{-2} yr^{-1} and the total PAR is extremely low (~350 grains cm^{-2} yr^{-1}). *Betula pubescens* macrofossils establish a continuous presence from *c*. 8200 cal. yr BP. By *c*. 7900 cal. yr BP *Betula* pollen percentages reach *c*. 80 % and the *Betula* PAR is between ~1500 and 2000 grains cm^{-2} yr^{-1}. The *Betula* PAR declines gradually after *c*. 6000 cal. yr BP and remains <1000 grains cm^{-2} yr^{-1} after 4200 cal. yr BP. *Sorbus aucuparia* pollen appear for the first time in the record *c*. 6000 cal. yr BP. Variations in OM, MS and DBD increase during this period, especially after *c*. 4000 cal. yr BP, with DBD ~0.12–0.18 g cm^{-3} and OM ~30–38 %.

3.2 Barðalækjartjörn (Paper II)

The period *c*. 10,300-8000 cal. yr BP is characterised by relatively high percentages of Cyperaceae (~20-40 %) and *Betula* (>25 %). *Betula nana* fruits, leaves and catkin scales are continuously recorded, with occasional occurrences of *Betula pubescens* fruits. Mean *Betula* pollen diameters measure about 18 µm within this zone. The total carbon (%TC) is initially low, between ~1 and 8 % and increases to ~20 % by *c*. 8000 cal. yr BP. *Betula* pollen increase to ~55-69 % of total land pollen between *c*. 8000 and 6700 cal. yr BP and the *Betula* PAR increases to >500 grains cm^{-2} yr^{-1} by *c*. 7400 cal. yr BP and climbs to >900 grains cm^{-2} yr^{-1} between *c*. 7000 and 6700 cal. yr BP. *Betula* pollen diameters increase to ~21 µm *c*. 7800 cal. yr BP. The *Betula* PAR decreases to <500 grains cm^{-2} yr^{-1}

after *c*. 6500 cal. yr BP and to <250 grains cm^{-2} yr^{-1} after *c*. 6300 cal. yr BP. There is a shift to lower C/N ratios of ~15 by *c*. 7600 cal. yr BP. *Betula* pollen percentages are ~46-56 % between *c*. 6700-4200 cal. yr BP, while the PAR decreases to <500 grains cm^{-2} yr^{-1} after *c*. 6500 cal. yr BP. Cyperaceae pollen increase to >20 % after *c*. 5300 cal. yr BP. C/N ratios shift to higher values (>15.5) by *c*. 5400 cal. yr BP. *Betula* pollen percentages decrease to 40 % above the Hekla 4 tephra layer (*c*. 4200 cal. yr BP; Dugmore et al., 1995) and range between ~30 and 38 % from 3300 to 1000 cal. yr BP. Cyperaceae pollen increase to ~50 % by *c*. 2500 cal. yr BP. *Betula* pollen decrease to <25 % by *c*. 700 cal. yr BP and *Betula* pollen grain diameters decrease to ~20 µm. *Betula nana* macrofossils appear *c*. 4000 cal. yr BP. *Sporormiella*-type spores (dung fungi) are recorded *c*. 700 cal. yr BP. DBD increases to values above 0.33 g cm^{-3} *c*. 1000 cal. yr BP and a similar trend is reflected in the MS record.

3.3 Bungutjörn

The earliest plant macrofossils recorded in the Bungutjörn core between *c*. 10,500 and 10,300 cal. yr BP are remains of *Empetrum nigrum*, *Salix herbacea*, and fruits of *Ranunculus confervoides* (Figure 3.1). MS values are stable, DBD is ~0.23-0.26 g cm^{-3} and OM ~11-13 %. Above the Saksunarvatn tephra *Empetrum nigrum* remains are most prominent in the macrofossil record. Other macrofossils are *Salix* spp. (including *S. herbacea* and *S. phylicifolia*), *Alchemilla* spp. fruits and various *Carex* fruits, *Luzula* and *Juncus* seeds and *Ranunculus confervoides* fruits. MS values increase above the tephra and OM increases from ~3 % immediately above the tephra to ~11 % by *c*. 10,000 cal. yr BP. *Betula nana* macrofossils appear in the record *c*. 8200 cal. yr BP. Organic matter is highest in the core between *c*. 7000 and 5000 cal. yr BP. Macrofossils from herbs such as *Carex* spp. and *Alchemilla* spp. disappear after *c*. 6000 cal. yr BP, while macrofossils of *Empetrum nigrum*, *Betula nana* and *Salix* spp. are present until the end of the record. Only two *Betula pubescens* macrofossils are recorded during the Holocene, a catkin scale *c*. 7400 cal. yr BP and a fruit *c*. 4500 cal. yr BP. MS begins to increase after *c*. 6600 cal. yr BP, while DBD begins to increase after *c*. 4200 cal. yr BP from ~0.2 to 0.3 g cm^{-3}. MS values increase again *c*. 2000 cal. yr BP and DBD increases to ~0.5 g cm^{-3}. The DBD begins to decrease *c*. 1000 cal. yr BP. OM is extremely low (~6-8 %) between *c*. 2000 and 1000 cal. yr BP, but increases towards the end of the record (Figure 3.1).

3.4 Stóra-Búrfell

The oldest plant macrofossils recorded in the Stóra-Búrfell core (Figure 3.2) are *Carex nigra* fruits, *Sphagnum* leaves and *Selaginella selaginoides* megaspores between *c*. 8900 and 8600 cal. yr BP. A *Betula* fruit with characteristics intermediate between *Betula nana* and *Betula pubescens* is first recorded *c*. 8500 cal. yr BP and macrofossils with intermediate morphologies are recorded until *c*. 6000 cal. yr BP. *Betula nana* macrofossils appear in the record *c*. 8300 cal. yr BP. *Betula pubescens* macrofossils are recorded from *c*. 7600 to 5800 cal. yr BP. *Sphagnum* leaves almost disappear from the record after 7100 cal. yr BP. Although high between *c*. 8900 and 8600 cal. yr BP, MS and DBD are relatively low and stable throughout the record, with peaks corresponding to tephra layers (Figure 3.2). A high number of leaves of *Calliergonella cuspidata* moss are recorded directly under the Hekla 4 tephra.

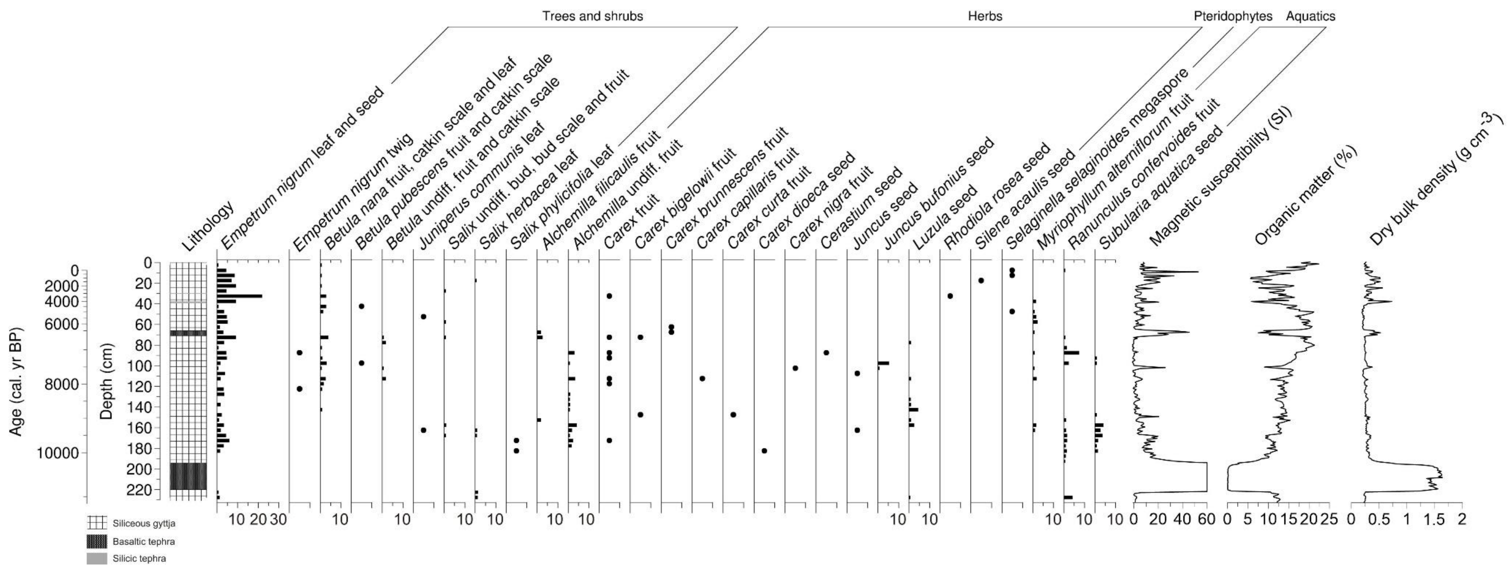

Figure 3.1 Plant macrofossil diagram for Bungutjörn. Including magnetic susceptibility (MS), organic matter (OM) and dry bulk density (DBD). Macrofossil concentrations in 50 ml. Dots signify concentrations <1.

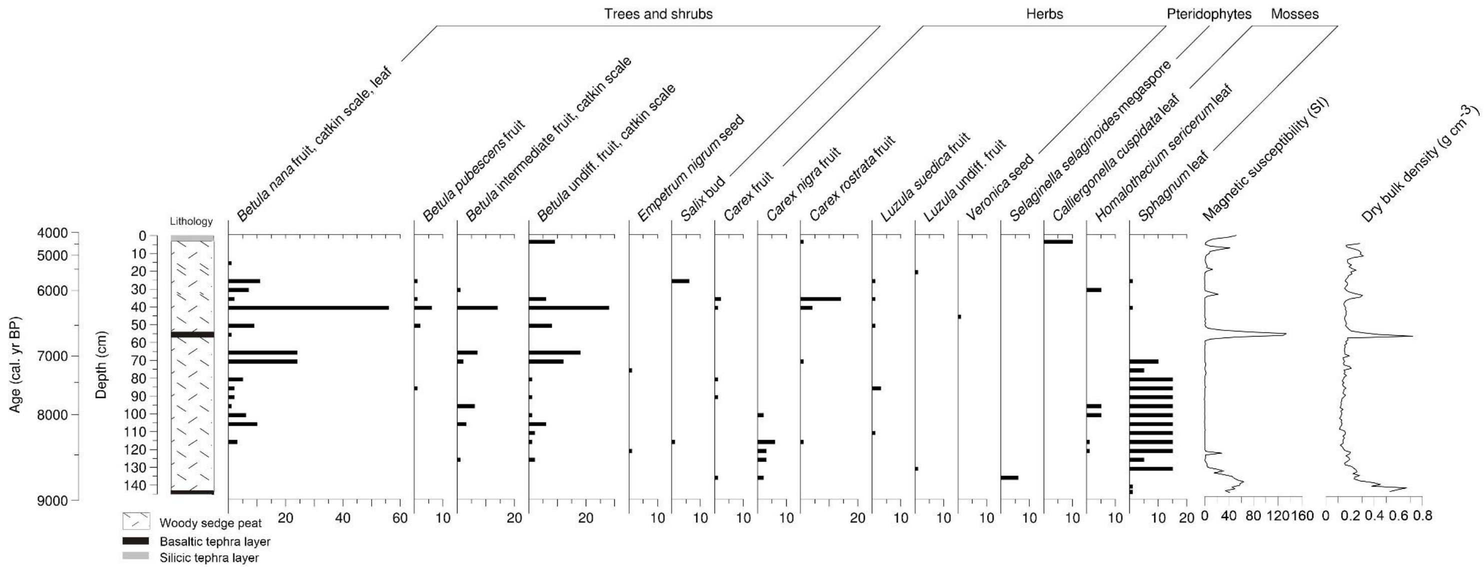

Figure 3.2 Plant macrofossil diagram for the Stóra-Búrfell peat core. Including magnetic susceptibility (MS) and dry bulk density (DBD).

3.5 Dating new (and old) tephra markers

Two new potential tephra markers for North Iceland were identified in cores used for this study, one from the Katla volcanic system (**Paper I**) and one of unknown origin (**Paper II**). Additionally, a new date for the Hekla 5 tephra was obtained (**Paper II**).

A dark tephra layer (Katla S; **Paper I**) was observed in numerous peat sequences and in three lake cores in Austur-Húnavatnssýsla, between the Hekla Ö (6060 cal. yr BP; Gudmundsdóttir et al., 2011b) and Hekla 5 tephra layers (7055 cal. yr BP; Thorarinsson, 1971). The tephra layer forms a distinct, dark, and relatively coarse grained stratum in organic sequences. The geochemical fingerprint is that of the Katla volcanic system (Figure 3.3). The tephra layer was dated using a *Betula* sp. twig and one *Salix* sp. twig situated directly below the tephra in a peat sequence from Stóra-Búrfell (Figure 2.1). The two analyses provide a mean date of 6592 ± 78 cal. yr BP (**Paper I**).

A second previously undated tephra layer (HUN; **Paper II**) was found between the Hekla 4 (Dugmore et al., 1995) and Hekla Ö tephra layers (Gudmundsdóttir et al., 2011b) in two peat sections and two lake cores. The geochemical fingerprint is of unknown origin (Figure 3.3). Two samples of wood in direct contact with the tephra were taken from a peat section at Neðri Mýrar (Figure 2.1). Both samples yielded the same calibrated age of 5530 ± 59 cal. yr BP.

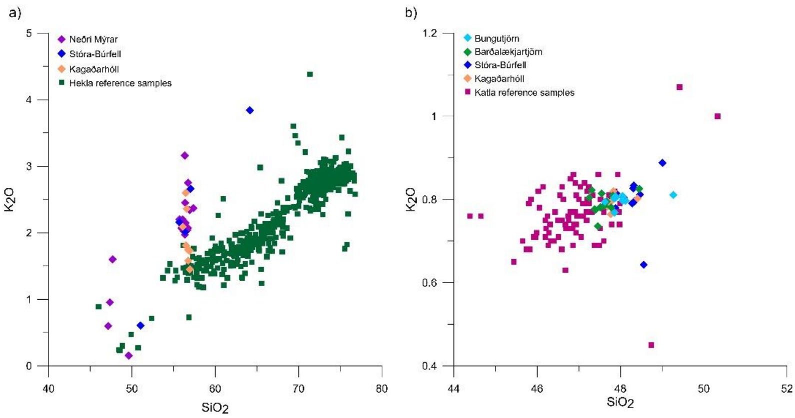

Figure 3.3 Glass analysis of new tephra markers for Austur-Húnavatnssýsla. HUN tephra a) plotted on reference a field for Hekla (Boygle, 1995; Dugmore and Newton, 1997; Dugmore and Newton, 1992; Dugmore and Newton, 1995; Dugmore et al., 1992; Gudmundsdóttir et al., 2011b; Hall and Pilcher, 2002; Larsen et al., 1999; Lawson et al., 2007; Pilcher et al., 2005; Pilcher and Hall, 1996; Pilcher et al., 1995; Pilcher et al., 1996; Streeter and Dugmore, 2014; Swindles, 2006; Wastegård et al., 2001; Zillén et al., 2002) and Katla S tephra b) plotted on reference a field for Katla (Boygle, 1995; Streeter and Dugmore, 2014).

The Hekla 5 tephra layer was dated by Thorarinsson (1971) to 7055 ± 255 cal. yr BP (2σ error for calibrated dates). In an attempt to improve the accuracy of the date, *Rhytidiadelphus squarrosus* mosses in direct contact with the tephra were collected from Trjáviðarlækur in Þjórsárdalur valley, about 14 km NW of the Hekla volcano in South Iceland (**Paper II**). The mosses extracted from the moss-tephra boundary below the tephra layer were well preserved. Radiocarbon dating yielded a calibrated age of 7063 ± 102 cal. yr BP.

4 Discussion

4.1 Holocene vegetation and environment in Northwest Iceland

4.1.1 Early Holocene

The earliest vegetation record from Iceland is from Skagi peninsula and extends back to *c*. 13,200 cal. yr BP. The record shows that dwarf shrub heath had already developed there during the Allerød interstadial, but was replaced by grasses and fell-field herbs (Rundgren, 1995) during the Younger Dryas glacier advance (*c*. 13.000-11,500 cal. yr BP; Ingólfsson et al., 2010). *Salix* and *Empetrum nigrum* dwarf shrub heath recovered after *c*. 10,700 cal. yr BP (Rundgren, 1995). This is supported by the Bungutjörn record which begins *c*. 10,600 cal. yr BP (Figure 3.1), where the earliest macrofossils are remains of *Empetrum nigrum* which grows in various habitats, including rocky surfaces (Kristinsson, 2010), and *Salix herbacea* which is associated with colonisation of nutrient poor soils in front of retreating glaciers (Beerling, 1998). The low MS and DBD in the Bungutjörn core during the early Holocene reflect a relatively stable environment around Bungutjörn (Figure 3.1), a result of a long continuous period of vegetation development in the area beginning during the Allerød interstadial (Rundgren and Ingólfsson, 1999).

The Kagaðarhóll record begins *c*. 11,000 cal. yr BP (**Paper I**), after the ice sheet of the Younger Dryas stadial retreated (Norðdahl et al., 2008). Environmental conditions were extremely unstable during the early Holocene, based on high MS and DBD values. The earliest pollen assemblage was dominated by grasses, herbs and pioneer taxa such as *Oxyria digyna*. The harsh, sparsely vegetated environment is reflected in extremely low PARs. After *c*. 10,800 cal. yr BP dwarf shrub heath began to develop with an increase in *Empetrum nigrum* pollen and a subsequent increase in *Salix* pollen by *c*. 10,600 cal. yr BP. The change towards dwarf shrub heath led to increasing vegetation cover and increased environmental stability, reflected in decreasing DBD and MS values by *c*. 10,500 cal. yr BP (**Paper I**).

4.1.2 Saksunarvatn tephra

The environment was widely affected by the deposition of the Saksunarvatn tephra, probably a result of series of eruptions originating from the Grímsvötn volcanic system (Jennings et al., 2014; Larsen and Eiriksson, 2008). The effects of the tephra on vegetation at Kagaðarhóll lasted for *c*. 100 years (**Paper I**). A similar response period is seen in other records from North Iceland (Caseldine et al., 2006; Rundgren, 1998). The following millennium was characterised by environmental instability, reflected in relatively high and fluctuating MS and DBD values (**Paper I**). Increased instability is seen in the Bungutjörn record as well where MS and DBD are higher than before the Saksunarvatn tephra until *c*. 9000 cal. yr BP (Figure 3.1).

The Barðalækjartjörn record at the highland margin begins above the Saksunarvatn tephra. The pollen record shows that *Betula nana* dwarf shrub heath established at the highland margin after the Saksunarvatn tephra fell. After the tephra was deposited the pollen assemblage shows indications of aeolian activity influencing the vegetation community. The composition of the pollen and macrofossil assemblages may suggest that dwarf shrubs were already growing in the highlands before the Saksunarvatn tephra and that vegetation survived both the deposition and subsequent aeolian reworking of the tephra (**Paper II**).

4.1.3 *Juniperus communis* and early birch woodland

At Kagaðarhóll, high PAR values (1000-3000 grains cm^{-2} yr^{-1}) for *Juniperus communis* from *c*. 10,100 to *c*. 9000 cal. yr BP suggest that a taller growth form of the species, rather than the prostrate shrubs found in Iceland today, grew around the lake (Birks, 1973). This may serve as indication of warm climate in Iceland during the early Holocene as tall *Juniperus communis* plants require higher temperatures than the lower growing shrubs (Kolstrup, 1980). A similar peak in *Juniperus communis* is seen in other records from North Iceland (Caseldine et al., 2006; Hallsdóttir, 1995; Rundgren, 1998). This is in agreement with chironomid inferred July temperature (Ci-T) reconstructions from North Iceland that have suggested warmer conditions than today between *c*. 10,500 and 8500 cal. yr BP (Langdon et al., 2010). This suggests that environmental development in North Iceland followed solar insolation closely during the early Holocene (**Paper I**). *Betula pubescens* woodland replaced the *Juniperus communis* scrub near Kagaðarhóll *c*. 9300 cal. yr BP, indicated by a decrease in *Juniperus communis* pollen, a relative increase in *Betula* pollen and a high concentration of *Betula pubescens* macrofossils. The development of woodlands led to more stable environmental conditions in the lowland, evidenced by decreasing MS and DBD (**Paper I**).

While woodland began to form in the lowland *Betula nana* dwarf shrub heath was the dominant vegetation community at the highland margin. Conditions at Barðalækjartjörn became progressively more stable after *c*. 9100 cal. yr BP, with decreasing MS and DBD (**Paper II**). During this period the macrofossil record from Bungutjörn was dominated by *Empetrum nigrum*, *Salix herbacea*, *S. phylicifolia* and *Alchemilla* spp., indicating a relatively stable dwarf shrub heath near the lake (Figure 3.1).

4.1.4 Cooling climate and reduced woodland

Increased instability is recorded at the highland margin *c*. 8900 cal. yr BP with increasing DBD and MS values (**Paper II**). This is followed by a decrease in the *Betula* PAR at Kagaðarhóll from values of ~1000 grains cm^{-2} yr^{-1} *c*. 9100 cal. yr BP to <200 grains cm^{-2} yr^{-1} by *c*. 8700 cal. yr BP. A decrease in total land PAR is also detected in a record from Skagafjörður, North Iceland (Hallsdóttir, 1995). The decrease in PARs probably represents a decrease in pollen production, in particular that of *Betula* pollen and this may have been caused by low spring and summer temperatures. This coincides with a cool period observed in other records from West Iceland and the central highlands (Geirsdóttir et al., 2013; Larsen et al., 2012). (**Paper I**). A comparable change in the pollen assemblage is not seen in the Barðalækjartjörn record where dwarf shrub heath, a hardier ecosystem than birch woodland was established (**Paper II**). The woodland at Kagaðarhóll began to recover after *c*. 8200 cal. yr BP (**Paper I**).

The Stóra-Búrfell record begins *c*. 9000 cal. yr BP and is initially characterised by relatively high influx of minerogenic material indicated by high MS and DBD. Macrofossils are first recorded *c*. 8600 cal. yr BP and leaves of *Sphagnum* moss and fruits of wetland sedges *Carex nigra* and *Carex rostrata* indicate the development of wetland (Figure 3.2). Hybridisation between *Betula nana* and *Betula pubescens* is evident from Icelandic pollen records from the early Holocene (Eddudóttir et al., 2015, 2016; Karlsdóttir, 2014; Karlsdóttir et al., 2009, 2012) and this is confirmed by the presence of macrofossils with morphologies intermediate between *Betula nana* and *Betula pubescens* from *c*. 8500 cal. yr BP. *Betula nana* macrofossils appear later in the record, around *c*. 8300 cal. yr BP (Figure 3.2).

4.1.5 Birch woodland maximum

The woodland at Kagaðarhóll recovered and reached its peak *c*. 7900 cal. yr BP with a relative increase in *Betula* pollen to >80 % and *Betula* PAR >1500 grains cm^{-2} yr^{-1} (**Paper I**). Birch woodland formed later at Barðalækjartjörn, where the increase in relative abundance of *Betula* pollen and a transition to larger *Betula* pollen diameters around *c*. 7800 cal. yr BP signal a shift from *Betula nana* to *Betula pubescens*. Formation of *Betula pubescens* woodland is indicated by an increase in *Betula* PAR to >500 grains cm^{-2} yr^{-1} between 7400 and 6500 cal. yr BP, peaking to values of >900 grains cm^{-2} yr^{-1} between *c*. 7000-6700 cal. yr BP (**Paper II**). The *Betula pubescens* woodland maximum at Barðalækjartjörn coincides with a similar peak at 400-450 m a.s.l. on Tröllaskagi peninsula (Wastl et al., 2001).

After *c*. 7100 cal. yr BP *Sphagnum* leaves almost disappear from the Stóra-Búrfell wetland, perhaps indicating drier conditions. *Betula pubescens* fruits are recorded in the peat from c. 7600 to 5800 cal. yr BP, indicating that *Betula pubescens* plants may have been able to grow in the wetland, at least in its drier parts (Figure 3.2). Continued hybridisation between *Betula nana* and *Betula pubescens* is evidenced by macrofossils with morphologies intermediate between the two species recorded until *c*. 6000 cal. yr BP.

Betula nana macrofossils are recorded at Bungutjörn after *c*. 8200 cal. yr BP. This indicates a change towards a *Betula nana*-*Empetrum nigrum* dwarf shrub heath on Skagi peninsula as woodlands developed further inland (Figure 3.1). *Betula pubescens* woodland probably did not colonise the area near Bungutjörn during the Holocene, even though tritherm temperatures on Skagi peninsula today are higher (Table 2.1) than the tritherm temperture threshold of 7.9°C for the 2 m treeline in Iceland (Wöll, 2008). Proximity to the ocean is a possible explanation, as oceanity and chloride content in groundwater can influence the location of treelines in Iceland (Wöll, 2008). There is evidence that oceanity influenced the chemistry of wetland soils on the western side of Skagi peninsula during the Holocene (Möckel, 2016). The oceanic contribution to soils in Skagi peninsula could therefore have prevented the development of woodlands even though summer temperatures may have been sufficiently high (Table 2.1).

4.1.6 Woodland decline

The decline of the woodland near Barðalækjartjörn began after *c*. 6700 cal. yr BP, indicated by a decrease in the *Betula* PAR from >900 to ~500 grains cm^{-2} yr^{-1} by *c*. 6500 cal. yr BP. Extremely low *Betula* PAR of <250 grains cm^{-2} yr^{-1} recorded at

Barðalækjartjörn after *c*. 6300 cal. yr BP should indicate that woodland had retreated from the site (Hicks, 2001). However, an increase in *Betula* pollen grain diameters indicates continued presence of *Betula pubescens* and no *Betula nana* macrofossils are recorded before *c*. 4000 cal. yr BP. This suggests that *Betula pubescens* was still the dominant *Betula* species in the area around Barðalækjartjörn (**Paper II**). The extremely low *Betula* PAR is probably a result of suppressed pollen production of *Betula pubescens* as the species was growing at, or near, its ecological limit (Birks and Bjune, 2010; Kuoppamaa et al., 2009). Low *Betula* PARs in woodlands have previously been noted in Icelandic pollen records (Erlendsson and Edwards, 2009).

The woodland at Kagaðarhóll began to decline after *c*. 6000 cal. yr BP and was in slow decline until the end of the record *c*. 2800 cal. yr BP. This is indicated by a decrease in *Betula* PAR from >1500 to ~1000 grains cm^{-2} yr^{-1} at *c*. 6000 cal. yr BP and to <1000 grains cm^{-2} yr^{-1} by *c*. 4200 cal. yr BP. During this period there is evidence of increased hybridisation between *Betula nana* and *Betula pubescens* in the form of an increase in non-triporate *Betula* pollen (Karlsdóttir, 2014), as *Betula nana* encroached on the *Betula pubescens* woodland (**Paper I**).

Very few macrofossils are recorded at Stóra-Búrfell after *c*. 5800 cal. yr BP, except for a large number of leaves of the moss *Calliergonella cuspidata* that were found directly beneath the Hekla 4 tephra. This could suggest a return to wetter conditions. An increase in minerogenic material deposited in the wetland is seen from an increase in DBD *c*. 5700 cal. yr BP and MS *c*. 5600 cal. yr BP (Figure 3.2). The Stóra-Búrfell record ends at the Hekla 4 tephra (4200 cal. yr BP; Dugmore et al., 1995)

The environment around Bungutjörn was characterised by *Empetrum nigrum-Betula nana* dwarf shrub heath at the time of woodland decline further inland. Very few macrofossils of herbs species are recorded after *c*. 6300 cal. yr BP. Increased environmental instability is reflected in fluctuations in MS above the Katla S tephra layer deposited *c*. 6600 cal. yr BP. Elevated MS values between *c*. 6300 and 4200 cal. yr BP (Figure 3.1) probably represent increasingly unstable environmental conditions in response to cooling climate.

4.1.7 The Hekla 4 tephra

The Hekla 4 tephra (4200 cal. yr BP; Dugmore et al., 1995) caused changes in the vegetation community at Kagaðarhóll (**Paper III**). The pollen assemblage immediately after the tephra is markedly different from that before, indicated by an increase in *Betula* pollen and the disappearance of herb pollen. This may indicate burial of the understory of the woodland by thick tephra deposits. This is similar to the effects of 12-15 cm thick tephra deposits from the 1980 eruption of Mount St. Helens which destroyed virtually all herbaceous plants (Antos and Zobel, 2005; Zobel and Antos, 2007). Thick tephra deposits can also hinder regrowth of plants, even creating a crust which buried plants cannot penetrate (Mack, 1987). Conversely, the new substratum created by a tephra layer can present opportunities for pioneer plants to colonise the new surface, which can lead to changed species composition (Antos and Zobel, 2005). *Betula* PAR of ~800-900 grains cm^{-2} yr^{-1} and *Betula* pollen diameters ~22 ± 2 μm both before and after the eruption, suggest that although the understory was buried the birch population was not affected by the tephra fall. Herb pollen taxa reappear in the record after a minimum period of 50 years after the eruption and this probably represents the recovery of the understory vegetation.

Overall, the stable woodland at lake Kagaðarhóll was able to recover relatively quickly to a state similar to that before the eruption despite burial of understory vegetation.

The Hekla 4 tephra is a major boundary between vegetation communities in the Barðalækjartjörn record (**Paper III**). The most noticeable change above the tephra is the decrease in *Betula* pollen percentages and PAR, accompanied by a wider range of *Betula* pollen diameters and an increase in pollen grains with diameters of 17 and 18 µm, more likely derived from *Betula nana* (Mäkelä, 1996). *Betula nana* macrofossils appear in the macrofossil record at the same time. Conditions probably became more difficult for *Betula pubescens* as a consequence of the tephra because the species was already under stress before the eruption. Further indication of a change from open birch woodland to dwarf shrub heath is an increase in the pollen of dwarf shrubs *Empetrum nigrum* and *Vaccinium*-type after *c*. 4200 cal yr BP. Indeed, woodland did not return to the vicinity of Barðalækjartjörn following the deposition of the Hekla 4 tephra. The tephra fell during a time of irreversible cooling *c*. 4200 cal. yr BP identified in several lake records (Blair et al., 2015; Geirsdóttir et al., 2013; Larsen et al., 2012). Cold climate can affect the recovery of ecosystems and prevent a return to a previous state following tephra fall (Arnalds, 2013) and the combination of cooling climate and the effects of the tephra fall may have facilitated the vegetation changes seen at Barðalækjartjörn. An ecosystem already under stress due to cooling climate gave way to more resilient dwarf shrub heath after the tephra fell at Barðalækjartjörn.

Vegetation cover and structure are important factors in stabilising tephra deposits and the capacity of vegetation to trap tephra increases with height (Arnalds, 2013; Cutler et al., 2016). About 4200 cal. yr BP, at the time of the Hekla 4 eruption, the Icelandic lowlands were probably covered by woodlands and mires (Eddudóttir et al., 2015; Hallsdóttir, 1995; Hallsdóttir and Caseldine, 2005) while open woodland, wetlands and dwarf shrub heath covered the highlands (Eddudóttir et al., 2016; Wastl et al., 2001). Stable environments such as these would have been able to entrap a large proportion (Arnalds, 2015; Cutler et al., 2016) of the tephra that fell during the eruption (Larsen and Thorarinsson, 1977). Today, around 42 % of Iceland is classified as desert and only 1.2 % is covered by natural birch woodlands (Gísladóttir et al., 2014). When tephra is deposited on barren or scarcely vegetated surfaces it is readily redistributed (Arnalds et al., 2013; Cutler et al., 2016) and deposits of only a few centimetres thickness can have negative environmental impacts (Arnalds et al., 2013). The results underscore the importance of vegetation cover in the event of heavy tephra fall.

4.1.8 Late Holocene and human settlement

Environmental instability began *c*. 6600 cal. yr BP at Skagi peninsula, higher MS values indicate an increase in minerogenic material deposited in Bungutjörn. Higher DBD is observed following the Hekla 4 tephra *c*. 4200 cal. yr BP. Both MS and DBD values increase further *c*. 2000 cal. yr BP, accompanied by a drop in OM (Figure 3.1). The same trend of higher MS values *c*. 2000 cal. yr BP is seen in a peat core from Torfdalsmýri on the western side of Skagi peninsula and in a peat core from Tindar, midway between Kagaðarhóll and Stóra-Búrfell (Möckel, 2016). These records all suggest increased instability in the lowland of Austur-Húnavatnssýsla beginning *c*. 2000 cal. yr BP and the decrease in OM in Bungutjörn suggests that lake productivity decreased as well, probably in response to cooling climate (Larsen et al., 2011, 2012; Striberger et al., 2012).

After *c*. 4200 cal. yr BP the vegetation community at Barðalækjartjörn was characterised by *Betula nana* dwarf shrub heath, with scattered *Betula pubescens* trees. There is evidence of increased instability after *c*. 4200 cal. yr BP as MS and DBD increase (**Paper II**). Greater instability is also reflected in increased MS measured in a peat core from Hrafnabjörg about 7 km west of Barðalækjartjörn at ~300 m a.s.l. (Möckel, 2016). However, the pollen assemblage at Barðalækjartjörn suggests that the vegetation community was relatively stable from *c*. 4200 cal. yr BP until about 1000 cal. yr BP, when human activities began to influence vegetation. The introduction of an additional driver of environmental change led to increased environmental instability, reflected in increasing MS and DBD, as well as the disappearance of ligneous species such as *Juniperus communis* and *Betula pubescens* from the highland margin (**Paper II**).

5 Conclusions

The vegetation and environment in Austur-Húnavatnssýsla, Northwest Iceland, have undergone great changes during the last 11,000 years; from the inhospitable fell-fields in the wake of the Younger Dryas ice sheet, to the birch woodlands of the mid Holocene, and finally the unstable environment created by human activities during the past 1000 years. The study shows that:

1. Climate has been the primary driver of vegetation changes in the lowland for most of the Holocene, with the warmest periods between 10,100-8700 cal. yr BP and 8000-6000 cal. yr BP. Vegetation development in the lowland was interrupted by the Saksunarvatn tephra and environmental conditions were relatively unstable for a millennium following the deposition of this tephra. *Juniperus communis* shrubs or trees were the dominant feature of the vegetation during the warm early Holocene. Birch woodland developed in the lowland by *c*. 9300 cal. yr BP, with an optimum period between *c*. 8000 and 6000 cal. yr BP. The woodland was in decline after *c*. 6000 cal. yr BP due to cooling climate.
2. The Barðalækjartjörn record is the first complete Holocene vegetation reconstruction representing the central highlands and gives an insight into a relatively stable environment for a large part of the Holocene and a glimpse of the catastrophic impact human settlement had on the sensitive environment of the Icelandic highlands. Vegetation development was slower at the highland margin than in the lowland. Dwarf shrub heath was replaced by birch woodland *c*. 7800 cal. yr BP. The woodland persisted until *c*. 4200 cal. yr BP, although low *Betula* PAR suggest that the woodland was at its ecological limit for most of that time, with the exception of a brief warm period between *c*. 7400 and 6500 cal. yr BP. Dwarf shrub heath replaced the open woodland after *c*. 4200 cal. yr BP, following the Hekla 4 eruption in response to cooling climate and the impact of the tephra fall. Human settlement began to influence the environment at the highland margin *c*. 1000 cal. yr BP, reflected in changes in the vegetation assemblage and landscape stability.
3. No evidence of birch woodland was found in the Bungutjörn record from Skagi peninsula. The macrofossil evidence suggests that the lake was surrounded by *Empetrum nigrum* dominated dwarf shrub heath for the entire Holocene. The absence of birch is probably due to proximity to the ocean influencing growth conditions.
4. The Hekla 4 tephra had an impact on both stable open woodland at Kagaðarhóll and open woodland under stress at Barðalækjartjörn. Although the woodland at Kagaðarhóll recovered after a minimum period of 50 years, the vegetation community at Barðalækjartjörn passed a tipping point and the struggling woodland was replaced by a hardier, more resilient ecosystem.

The multi-site, multi-proxy approach adopted in this study has delivered a clear regional picture of the environmental changes in Austur-Húnavatnssýsla (Figure 5.1) where vegetation changes were asynchronous between sites as a result of their different environmental settings.

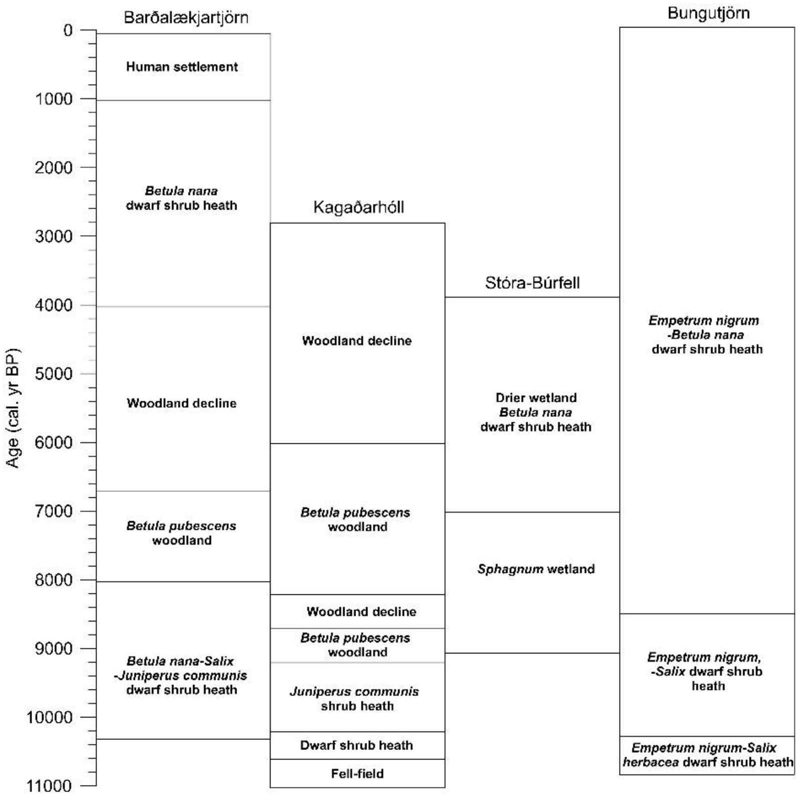

Figure 5.1 Vegetation changes recorded at all four sites.

The study shows the advantages of combining plant macrofossil analysis and pollen analysis for more robust vegetation reconstructions of both regional and local vegetation changes. These proxies combined with lithological proxies for organic and inorganic matter deposition provide ample material for environmental reconstructions. With the large amount of tephra markers stored in sediments and soils, Iceland offers the unique opportunity to combine paleoenvironmental records. Vegetation reconstructions from small lakes, high resolution geochemical analysis of sediments from larger basins, and paleosols can form the basis for robust environmental reconstructions. Such integrated approaches to paleoecological reconstructions could be the key to understanding the complex interplay of climate and volcanism at important turning points in Iceland's environmental history e.g. cooling episodes coinciding with large volcanic eruptions.

The environmental reconstructions presented in this thesis have improved the understanding of the responses of the Icelandic environment to external forcing mechanisms as climate, tephra fall and human activities. The Barðalækjartjörn record is the first Holocene vegetation reconstruction from the central highlands and shows that the highland environment, at least at the highland margin was relatively resilient to cooling climate until human settlement. This study underscores, once again, the immense environmental impact that humans have had on the Icelandic environment. Although relying on traditional methods for vegetation reconstructions this study presents the first full Holocene records of pre-settlement PARs. *Betula* PAR in particular provides additional information about vegetation changes and may even be a more accurate measure of features such as the state of birch woodlands. To improve the understanding of the extent of the impact climate change, tephra deposition and land use have on terrestrial ecosystems, vegetation reconstructions are essential. The knowledge garnered within this thesis provides an important base for further studies of Holocene environmental changes in Iceland.

References

Alley, R. B. and Ágústsdóttir, A. M. (2005). The 8k event: cause and consequences of a major Holocene abrupt climate change. *Quaternary Science Reviews*, *24*(10), 1123-1149.

Alley, R. B., Mayewsk,i P. A., Sowers, T., Stuiver, M., Taylor, K. C. and Clark, P. U. (1997). Holocene climatic instability: A prominent, widespread event 8200 yr ago. *Geology*, *25*(6), 483-486.

Antos, J. A. and Zobel, D. B. (2005). Plant responses in forests of the tephra-fall zone. In: V. H. Dale, F. J Swanson and C. M. Crisafulli (Eds.), *Ecological responses to the 1980 eruption of Mount St. Helens* (pp. 47-58). New York: Springer.

Arnalds, O. (2013). The influence of volcanic tephra (ash) on ecosystems. In: D. Sparks (Ed.), *Advances in Agronomy* (pp. 332-380). Amsterdam: Elsevier.

Arnalds, O. (2015). *The soils of Iceland*, Dordrecht: Springer.

Arnalds, O, Dagsson-Waldhauserova, P and Olafsson, H. (2016). The Icelandic volcanic aeolian environment: Processes and impacts — A review. *Aeolian Research*, *20*, 176-195.

Arnalds, O, Gisladottir, F and Sigurjonsson, H. (2001). Sandy deserts of Iceland: an overview. *Journal of Arid Environments*, *47*(3), 359-371.

Arnalds, O, Thorarinsdottir, E. F., Thorsson J., Waldhauserova, P. D. and Agustsdottir, A. M. (2013). An extreme wind erosion event of the fresh Eyjafjallajokull 2010 volcanic ash. *Scientific reports*, *3*, 1257. doi: 10.1038/srep01257

Ascough, P. L., Cook, G. T., Church, M. J., Dugmore, A. J., McGovern, T. G., Dunbar, E., . . . Gestsdottir, H. (2007). Reservoirs and radiocarbon: 14C dating problems in Myvatnssveit, Northern Iceland. *Radiocarbon*, *49*(2), 947-961.

Beerling, D. (1998). Salix herbacea L. *Journal of Ecology*, *86*(5), 872-895.

Bengtsson, L. and Enell, M. (1986). Chemical analysis. In: B. E. Berglund (Ed.), *Handbook of Holocene Palaeoecology and Palaeohydrology* (pp. 423-451). Chichester: John Wiley & Sons.

Bennett K.D. (2016). Catalogue of pollen types. Retrieved from http://www.chrono.qub.ac.uk/pollen/pc-intro.html.

Berggren, G. (1969). *Atlas of seeds and small fruits of Northwestern-European plant species (Sweden, Norway, Denmark, East Fennoscandia and Iceland) with morphological descriptions: Part 2 Cyperaceae*. Stockholm: Swedish Natural Science Research Council.

Birks, H. H. (2007). Plant Macrofossils - Introduction. In S. A. Elias (Ed.), *Encyclopedia of Quaternary Science* (2nd Edition) (pp. 2266-2288). Amsterdam: Elsevier.

Birks, H. H. and Bjune, A. E. (2010). Can we detect a west Norwegian tree line from modern samples of plant remains and pollen? Results from the DOORMAT project. *Vegetation history and Archaeobotany*, *19*(4), 325-340.

Birks, H. J. B. (1973). Modern pollen studies in some arctic and alpine environments. In: H. J. B. Birks and R. G. West (Eds.), *Quaternary Plant Ecology* (pp. 143-168). Oxford: Blackwell.

Björck, S., Ingólfsson, Ó., Hafliðason, H., Hallsdóttir, M. and Anderson, N. (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. and Kristersson, I. (1978). Comparison of two concentration methods for pollen in minerogenic sediments. *GFF*, *100*(1), 107-111.

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

Blair, C. L., Geirsdottir, A. and Miller, G. H. (2015). A high-resolution multi-proxy lake record of Holocene environmental change in southern Iceland. *Journal of Quaternary Science*, *30*(3), 281-292.

Boygle, J. E. (1995). *Tephra in lake sediments: an unambiguous geochronological marker?* (PhD thesis). Edinburgh: University of Edinburgh.

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

Campbell, J., Fletcher, W., Hughes, P. and Shuttleworth, E. L. (2016). A comparison of pollen extraction methods confirms dense-media separation as a reliable method of pollen preparation. *Journal of Quaternary Science*, *31*(6), 631-640.

Cappers, R. T. J., Bekker, R. M. and Jans, J. E. A. (2012). *Digitale Zadenatlas van Nederland*. Groningen: Barkhuis & Groningen University Library.

Caseldine, C., Geirsdóttir, Á. and Langdon, P. (2003). Efstadalsvatn–a multi-proxy study of a Holocene lacustrine sequence from NW Iceland. *Journal of Paleolimnology*, *30*(1), 55-73.

Caseldine, C., Langdon, P. and 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), 2314-2331.

Cutler, N. A., Bailey, R. M., Hickson, K. T., Streeter, R. T. and Dugmore, A. J. (2016). Vegetation structure influences the retention of airfall tephra in a sub-Arctic landscape. *Progress in Physical Geography*, *40*(5), 661-675.

Dearing, J. (1994). *Environmental magnetic susceptibility Using the Bartington MS2 system*. Kenilworth: Chi Publishing.

Dugmore, A. J. and Newton, A. J. (1992). Thin tephra layers in peat revealed by X-radiography. *Journal of Archaeological Science*, *19*(2), 163-170.

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

Dugmore, A. J. and Newton, A. (1997). Holocene tephra layers in the Faroe Islands. *Fróðskaparrit*, *45*, 141-154.

Dugmore, A. J., Church, M. J., Buckland, P. C., Edwards, K. J., Lawson, I., McGovern, T. H., . . . Sveinbjarnardóttir, G. (2005). The Norse landnám on the North Atlantic islands: an environmental impact assessment. *Polar Record*, *41*(1), 21-37.

Dugmore, A. J., Cook, G. T., Shore, J. S., Newton, A. J., Edwards, K. J. and Larsen, G. (1995). Radiocarbon dating tephra layers in Britain and Iceland. *Radiocarbon*, *37*(2), 379-388.

Dugmore, A. J., Gísladóttir, G., Simpson, I. A. and 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., Newton, A. J., Sugden, D. E. and Larsen, G. (1992). Geochemical stability of fine-grained silicic Holocene tephra in Iceland and Scotland. *Journal of Quaternary Science*, *7*(2), 173-183.

Eddudóttir, S. D., Erlendsson, E. and Gísladóttir, G. (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., Erlendsson, E., Tinganelli, L. and 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.

Eiríksson, J., Knudsen, K. L., Haflidason, H. and 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.

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

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

Erlendsson, E., Edwards, K. J. and 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.

Faegri, K., Kaland, P. E. and Krzywinski, K. (1989). *Textbook of Pollen Analysis*. New York: John Wiley & Sons.

Gathorne-Hardy, F. J., Erlendsson, E., Langdon, P. G. and 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.

Geirsdóttir, Á., Miller, G. H., Axford, Y. and Ólafsdóttir, S. (2009). Holocene and latest Pleistocene climate and glacier fluctuations in Iceland. *Quaternary Science Reviews*, *28*(21), 2107-2118.

Geirsdóttir, Á., Miller, G. H., Larsen, D. J. and Ólafsdóttir, S. (2013). Abrupt Holocene climate transitions in the northern North Atlantic region recorded by synchronized lacustrine records in Iceland. *Quaternary Science Reviews*, *70*, 48-62.

Gísladóttir, F. Ó., Brink, S. H. and Arnalds, Ó. (2014). Nytjaland (Icelandic Farmland Database). Agricultural University of Iceland Report 49. In Icelandic, English summary.

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

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

Grimm, E. C. (2011). TILIA 1.7.16. Springfield: Illinois state museum.

Gudmundsdóttir, E. R., Eiríksson, J. and Larsen, G. (2011a). Identification and definition of primary and reworked tephra in Late Glacial and Holocene marine shelf sediments off North Iceland. *Journal of Quaternary science*, *26*(6), 589-602.

Gudmundsdóttir, E. R., Larsen, G. and Eiríksson, J. (2011b). Two new Icelandic tephra markers: The Hekla Ö tephra layer, 6060 cal. yr BP, and Hekla DH tephra layer, ~6650 cal. yr BP. Land-sea correlation of mid-Holocene tephra markers. *The Holocene*, *21*(4), 629-639.

Gudmundsdóttir, E. R., Larsen, G. and Eiríksson, J. (2012). Tephra stratigraphy on the North Icelandic shelf: extending tephrochronology into marine sediments off North Iceland. *Boreas*, *41*(4), 719-734.

Hall, V. A. and Pilcher, J. R. (2002). Late-Quaternary Icelandic tephras in Ireland and Great Britain: detection, characterization and usefulness. *The Holocene*, *12*(2), 223-230.

Hallsdóttir, M. (1982). Frjógreining tveggja jarðvegssniða úr Hrafnkelsdal. Áhrif ábúðar á gróðurfar dalsins. In H. Þórarinsdóttir, Ó. H. Óskarsson, S. Steinþórsson and Þ. Einarsson (Eds.), *Eldur er í norðri* (pp. 253-265). Reykjavík: Sögufélag.

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

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

Hallsdóttir, M. and Caseldine, C. J. (2005). The Holocene vegetation history of Iceland, state-of-the-art and future research. In C. Caseldine, A. Russel, J. Harðardóttir and Ó. Knudsen (Eds.), *Iceland – modern processes and past environments* (pp. 319-334). Amsterdam: Elsevier.

Hicks, S. (2001). The use of annual arboreal pollen deposition values for delimiting tree-lines in the landscape and exploring models of pollen dispersal. *Review of Palaeobotany and Palynology*, *117*(1-3), 1-29.

Ingólfsson, Ó., Norðdahl. H. and Schomacker, A. (2010) 4 Deglaciation and Holocene Glacial History of Iceland. In A. Schomacker, J. Krüger Kurt and K. H. Kjær (Eds.), *Developments in Quaternary Sciences: Volume 13. The Mýrdalsjökull Ice Cap, Iceland. Glacial processes, sediments and landforms on an active volcano* (pp. 51-68). Amsterdam: Elsevier.

Jennings, A., Thordarson, T., Zalzal, K., Stoner, J., Hayward, C., Geirsdóttir, Á. and Miller, G. (2014). Holocene tephra from Iceland and Alaska in SE Greenland Shelf Sediments. In W. E. N. Austin, P. M. Abbott, S. M. Davies, N. J. G. Pearce and S. Wastegård (Eds.), *Marine Tephrochronology*. London: The Geological Society.

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

Karlsdóttir, L., Hallsdóttir, M., Thórsson, Æ. T. and Anamthawat-Jónsson, 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., Hallsdóttir, M., Thórsson, Æ. T. and Anamthawat-Jónsson, K. (2012). Early Holocene hybridisation between Betula pubescens and B. nana in relation to birch vegetation in Southwest Iceland. *Review of Palaeobotany and Palynology*, *181*, 1-10.

Katz, N. J., Katz, S. V. and Kipiani, M. G. (1965). *Atlas and keys of fruits and seeds occuring in the Quaternary deposits of the USSR*. Moscow: Publishing House Nauka.

Kirkpatrick, J., Enion, D. and Burd, D. (1995). Hydrofluoric acid burns: a review. *Burns*, *21*(7), 483-493.

Kolstrup, E. (1980). *Climate and stratigraphy in northwestern Europe between 30,000 BP and 13,000 BP with special reference to the Netherlands*. Haarlem: Rijks Geologische Dienst.

Kristinsson, H. (2010). *Flowering plants and ferns of Iceland*. Reykjavík: Mál og menning.

Kuoppamaa, M., Huusko, A. and 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*, *24*(5), 513-521.

Langdon, P. G., Leng, M., Holmes, N. and Caseldine, C. J. (2010). Lacustrine evidence of early-Holocene environmental change in northern Iceland: a multiproxy palaeoecology and stable isotope study. *The Holocene*, *20*(2), 205-214.

Larsen, D. J., Miller, G. H., Geirsdóttir, Á. and Thordarson, T. (2011). A 3000-year varved record of glacier activity and climate change from the proglacial lake Hvítárvatn, Iceland. *Quaternary Science Reviews*, *30*(19), 2715-2731.

Larsen, D. J., Miller, G. H., Geirsdóttir, Á. and 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 Reviews*, *39*, 14-25.

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

Larsen, G. and Eiriksson, J. (2008). Late Quaternary terrestrial tephrochronology of Iceland—frequency of explosive eruptions, type and volume of tephra deposits. *Journal of Quaternary Science*, *23*(2), 109-120.

Larsen, G. and Thorarinsson, S. (1977). H4 and other acid Hekla tephra layers. *Jökull*, *27*, 28-46.

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

Mack, R. N. (1987). Effects of Mount St Helens ashfall in steppe communities of eastern Washington: one year later. In D. E. Bilderback (Ed.), *Mount St Helens 1980 – Botanical Consequences of the Explosive Eruptions* (pp. 262-281). Berkeley: University of California Press.

Mäkelä, E. M. (1996). Size distinctions between Betula pollen types—a review. *Grana*, *35*(4), 248-256.

McGovern, T. H., Vésteinsson, O., Friðriksson, A., Church, M., Lawson, I., Simpson, I. A., . . . Perdikaris, S. (2007). Landscapes of settlement in northern Iceland: Historical ecology of human impact and climate fluctuation on the millennial scale. *American Anthropologist*, *109*(1), 27-51.

Moore, P. D., Webb, J. A. and Collison, M. E. (1991). *Pollen analysis*. Oxford: Blackwell scientific publications.

Möckel, S. C. (2016). *Environmental changes and development of the nutrient budget of Histosols in North Iceland during the Holocene* (MSc thesis). Reykjavík: University of Iceland.

Nakagawa, T., Brugiapaglia, E., Digerfeldt, G., Reille, M., De Beaulieu, J-L. and 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.

Norðdahl, H., Ingólfsson, Ó., Pétursson, H. G. and Hallsdóttir, M. (2008). Late Weichselian and Holocene environmental history of Iceland. *Jökull*, *58*, 343-364.

Oksanen, J., Blanchet, F. G., Kindt, R., Legendre, P., Minchin, P. R., O'Hara, R. B., . . . Wagner, H. (2016). vegan: Community Ecology Package. R package version 2.3-3. http:// CRAN.R-project.org/package=vegan

Óladóttir, B. (2009). *Holocene eruption history and magmatic evolution of the subglacial Vatnajökull volcanoes, Grímsvötn, Bárdarbunga and Kverkfjöll, Iceland* (PhD thesis). Clermont-Ferrand: Université Blaise Pascal and Reykjavík: University of Iceland.

Pilcher, J. R., Bradley, R. S., Francus, P. and Anderson, L. (2005). A Holocene tephra record from the Lofoten Islands, arctic Norway. *Boreas*, *34*(2), 136-156.

Pilcher, J. R. and Hall, V. A. (1996). Tephrochronological studies in northern England. *The Holocene*, *6*(1), 100-105.

Pilcher, J. R., Hall, V. A. and McCormac, F. G. (1995). Dates of Holocene Icelandic volcanic eruptions from tephra layers in Irish peats. *The Holocene*, *5*(1), 103-110.

Pilcher, J. R., Hall, V. A. and McCormac, F. G. (1996). An outline tephrochronology for the Holocene of the north of Ireland. *Journal of Quaternary Science*, *11*(6), 485-494.

Rasmussen, S. O., Andersen, K. K., Svensson, A. M., Steffensen, J. P., Vinther, B. M., Clausen, H. B., . . . Ruth, U. (2006). A new Greenland ice core chronology for the last glacial termination. *Journal of Geophysical Research: Atmospheres*, *111*(D6), D06102. doi:10.1029/2005JD006079

Reimer, P. J., Bard, E., Bayliss, A., Beck, J. W., Blackwell, P. G., Ramsey, C. B., . . . Friedrich, M. (2013). IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. *Radiocarbon*, *55*(4), 1869-1887.

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. *The Holocene*, *8*(5), 553-564.

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

Streeter, R. and Dugmore, A. (2014). Late-Holocene land surface change in a coupled social–ecological system, southern Iceland: a cross-scale tephrochronology approach. *Quaternary Science Reviews*, *86*, 99-114.

Striberger, J., Björck, S., Holmgren, S. and 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.

Swindles, G. (2006). *Reconstruction of Holocene climate change from peatland in the north of Ireland* (PhD thesis). Belfast: Queen's University.

Thomas, E. R., Wolff, E. W., Mulvaney, R., Steffensen, J. P., Johnsen, S. J., Arrowsmith, C., . . . Popp, T. (2007). The 8.2 ka event from Greenland ice cores. *Quaternary Science Reviews*, *26*(1), 70-81.

Thorarinsson, S. (1958). The Öræfajökull eruption of 1362. *Acta Naturalia Islandica* II. Reykjavík: Náttúrugripasafn Íslands.

Thorarinsson, S. (1971). The age of the light Hekla tephra layers according to corrected C14–datings. *Náttúrufræðingurinn*, *41*, 99-105.

Thordarson, T. and Larsen, G. (2007). Volcanism in Iceland in historical time: Volcano types, eruption styles and eruptive history. *Journal of Geodynamics*, *43*(1), 118-152.

Vasari, Y. (1972). The history of the vegetation in Iceland during the Holocene. In Y. Vasari, H. Hyvärinen and S. Hicks (Eds.), *Climatic Changes in Arctic Areas During the Last Ten-Thousand Years* (pp. 239-252). Oulu: University of Oulu.

Vasari, Y. (1973). Post-glacial plant succession in Iceland before the period of human interference. In N. A. Khotinsky (Ed.), *Palynology of Holocene, Proceedings of the III. International Palynological Conference* (pp. 7-14). Moscow: Publishing House Nauka.

Vasari, Y. and Vasari, A. (1990). L'histoire Holocéne des lacs Islandais. In J. Malaurie (Ed.), *102 témoignages en hommage á quarante ans d'études arctiques* (pp. 279-293). Paris: Éditions Plon.

Vickers, K., Erlendsson, E., Church, M.J., Edwards, K. J. and 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. *The Holocene*, *21*(6), 979-995.

Wastegård, S., Björck, S., Grauert, M. and Hannon, G. E. (2001). The Mjáuvøtn tephra and other Holocene tephra horizons from the Faroe Islands: a link between the Icelandic source region, the Nordic Seas, and the European continent. *The Holocene*, *11*(1), 101-109.

Wastl, M., Stötter, J. and 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.

Wöll, C. (2008). *Treeline of mountain birch (Betula pubescens Ehrh.) in Iceland and its relationship to temperature* (Diploma thesis in Forest Botany). Dresden: Technische Universität Dresden.

Zillén, L. M., Wastegård, S. and Snowball, I. F. (2002). Calendar year ages of three mid-Holocene tephra layers identified in varved lake sediments in west central Sweden. *Quaternary Science Reviews*, *21*(14), 1583-1591.

Zobel, D. B. and Antos, J. A. (2007). Flowering and seedling production of understory herbs in old-growth forests affected by 1980 tephra from Mount St. Helens. *Botany*, *85*(7), 607-620.

Paper I

Life on the periphery is tough: Vegetation in Northwest Iceland and its responses to early-Holocene warmth and later climate fluctuations

Research paper

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Life on the periphery is tough: Vegetation in Northwest Iceland and its responses to early-Holocene warmth and later climate fluctuations

Sigrún D Eddudóttir,[1] Egill Erlendsson[1,2,3] and Guðrún Gísladóttir[1,2,3]

Abstract

Long- and short-term climate variations in the North Atlantic have been of sufficient magnitude to leave a discernible mark on the history of vegetation and landscape stability in Iceland during the Holocene. A reconstruction of early- and mid-Holocene vegetation around Lake Kagaðarhóll, Northwest Iceland, examines how climate fluctuations have affected the terrestrial ecosystem. A thorough reconstruction has been made using pollen and plant macrofossil analyses combined with proxies for organic and inorganic matter. The record shows the development from a period of pioneer vegetation towards a woodland ecosystem. The deposition of the Saksunarvatn tephra at *c.* 10,300 cal. yr BP caused a 100-year period of instability, followed by a gradual trend of stabilization over several centuries while material left behind by retreating glaciers and tephra was being contained by expanding and developing vegetation. Early-Holocene warmth is indicated by high pollen production of *Juniperus communis* around the lake by *c.* 10,100 cal. yr BP and birch woodland being established around the lake by *c.* 9200 cal. yr BP, much earlier than previously believed for this locale. Cooling climate between *c.* 8700 and 8200 cal. yr BP halted woodland development, with reduced plant reproduction likely caused by cold spring and summer temperatures. Woodlands became re-established from *c.* 7900 cal. yr BP before entering a decline from *c.* 6000 cal. yr BP, with harsher environmental conditions apparent after *c.* 4200 cal. yr BP. The Kagaðarhóll record compares favourably with other palaeoclimatic data from the North Atlantic, demonstrating the potential of pollen and macrofossil data for reconstructions of environmental change in Iceland and as an indicator of climate variability in the North Atlantic during the Holocene.

Keywords

Betula, climate change, environmental change, Holocene, Iceland, landscape stability, macrofossils, North Atlantic, pollen, vegetation dynamics

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Introduction

In order to gain a better understanding of the potential effects of changing climate in the North Atlantic, an array of palaeoenvironmental reconstructions in key locations in the region is necessary. Iceland offers an excellent opportunity for the study of the effect of Holocene climate variability in the North Atlantic on terrestrial environments because of its location near atmospheric and oceanic boundaries. Prior to the Norse settlement in the late 9th century, Iceland was free of mammal herbivores, and terrestrial ecosystem developments were therefore dictated mainly by fluctuations in climate and, on shorter time scales, volcanism. Holocene climate variability around Iceland has been widely studied using marine sediments (e.g. Andresen et al., 2005, 2013; Castañeda et al., 2004; Eynaud et al., 2004; Giraudeau et al., 2004; Jennings et al., 2011; Justwan et al., 2008; Knudsen et al., 2004, 2008; Ran et al., 2006, 2008; Rousse et al., 2006) and a clearer picture of the pre-settlement history of the Icelandic terrestrial Holocene environment (e.g. Caseldine et al., 2003, 2006; Hallsdóttir, 1995; Wastl et al., 2001) and Holocene glacial activity (Geirsdóttir et al., 2009, 2013; Larsen et al., 2012; Striberger et al., 2012) is emerging.

The link between changes in North Atlantic ocean circulation, climate and the terrestrial environment in Iceland is reflected in historical records of sea-ice extent and its consequences for agriculture and human survival during the past centuries (Ogilvie, 1984; Ogilvie and Jónsdóttir, 2000; Ogilvie and Jónsson, 2001). The apparent sensitivity of the terrestrial ecosystem in Iceland provides ideal conditions for the study of Holocene climate variability in the region.

The natural climax vegetation in Iceland is downy birch (*Betula pubescens* Ehrh.), whose growth and distribution correlates with temperature (Jónsson, 2005; Wöll, 2008). The modern day *Betula pubescens* distribution limit in Iceland is located between 260 and 500 m a.s.l. and the tree line (for 2 m high trees) between 60 and 410 m a.s.l. The distribution limit is correlated with a summer tritherm temperature (mean of the three warmest

[1]Institute of Life and Environmental Sciences, University of Iceland, Iceland
[2]Faculty of Life and Environmental Sciences, University of Iceland, Iceland
[3]Institute of Earth Sciences, University of Iceland, Iceland

Corresponding author:
Sigrún D Eddudóttir, Institute of Life and Environmental Sciences, University of Iceland, Sturlugata 7, Reykjavík, 101, Iceland.
Email: sde6@hi.is

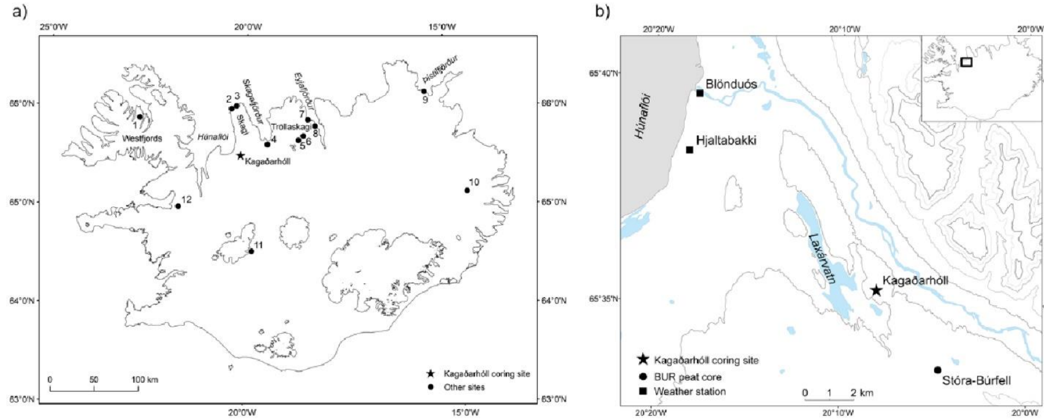

Figure 1. Maps showing the Kagaðarhóll coring site: (a) a map of Iceland showing the location of the Kagaðarhóll site and other Holocene records mentioned in the text. Site 1 Efstadalsvatn (Caseldine et al., 2003), sites 2 and 3 in Skagi peninsula (Björck et al., 1992; Rundgren, 1998), site 4 Vatnskotsvatn (Hallsdóttir, 1995), sites 5 and 6 (Wastl et al., 2001), sites 7 and 8 Tröllaskagi peninsula (Caseldine et al., 2006), site 9 Þistilfjörður (Karlsdóttir, 2014), site 10 Lake Lögurinn (Striberger et al., 2012), site 11 Hvítárvatn (Geirsdóttir et al., 2013; Larsen et al., 2012), site 12 Haukadalsvatn (Geirsdóttir et al., 2013) and (b) location of Kagaðarhóll, weather stations mentioned in the text and peat core (BUR) at Stóra-Búrfell.

summer months, June, July, August) of 7.2°C inland and the 2 m tree line with 7.9°C (Wöll, 2008). Evidence for the highest known tree lines of the Holocene date back to *c.* 7600–6800 cal. yr BP and are located between 400 and 450 m a.s.l. in Tröllaskagi peninsula, North Iceland (Wastl et al., 2001; Figure 1a). At this time, mean July temperatures at sea level at Tröllaskagi may have been up to 3°C higher than the mean 1961–1990 July temperature (Caseldine et al., 2006). This suggests that records of *Betula pubescens* in sediments in Iceland may serve as a thermometer, with increased occurrence of the taxon at higher elevations during periods of higher summer temperatures and with regressions during periods with colder summers. Reconstructions of Holocene forest dynamics before the Norse settlement may therefore provide important information about climate and environmental change in an environment free of anthropogenic interference, for example, woodland clearance, grazing livestock and so on.

Most of the existing Icelandic palynological datasets come from studies that have been conducted on peat cores (see Hallsdóttir, 1995; Hallsdóttir and Caseldine, 2005), while only a few studies of lake sediments are available (Björck et al., 1992; Caseldine et al., 2003, 2006; Erlendsson, 2007; Gathorne-Hardy et al., 2009; Hallsdóttir, 1995; Rundgren, 1995, 1998; Vasari, 1972, 1973; Vasari and Vasari, 1990). Instead of providing a long-term trajectory of climate-driven Holocene vegetation change, most studies have focused on shorter periods within the Holocene, such as the transition from the Late Glacial into the early Holocene and early plant colonization (Björck et al., 1992; Rundgren, 1995, 1998; Rundgren and Ingólfsson, 1999), establishing the timing of the Holocene Thermal Maximum (HTM) (Caseldine et al., 2006) and the environmental impact of human settlement after AD 870 (e.g. Erlendsson, 2007; Erlendsson and Edwards, 2009; Gathorne-Hardy et al., 2009; Gísladóttir et al., 2010, 2011; Lawson et al., 2007; Vickers et al., 2011). The analysis of plant macrofossils has not been widely applied for vegetation reconstructions in Iceland. Only five published studies have combined pollen analysis and plant macrofossil analysis as complementary methods (Erlendsson et al., 2012; Rundgren, 1998; Vasari and Vasari, 1990; Vickers et al., 2011; Wastl et al., 2001), despite the importance of plant macrofossils for the interpretation of pollen data (Birks and Birks, 2000). In addition, studies of modern processes in front of retreating glaciers in Iceland, such as primary plant succession and soil formation (Marteinsdóttir et al., 2007; Persson, 1964; Vilmundardóttir et al., 2014, 2015), as well as studies of the effects of aeolian sediment deposition on vegetation (Gisladottir et al., 2005; Vilmundardóttir et al., 2009) are now available for comparison with palaeoecological data.

This paper presents the history of early- and mid-Holocene vegetation development in Austur-Húnavatnssýsla, Northwest Iceland. Using pollen, plant macrofossils and proxies of organic and inorganic matter, we examine links between climate and environmental change, especially whether long- and short-term changes in climate have been of sufficient magnitude to leave discernible signals in records of vegetation and landscape stability in the Northwest lowlands of Iceland. The data presented derive from a lake sediment core from a lowland site near the farm Kagaðarhóll (Figure 1a) where present day climate conditions are appropriate for birch growth, although birch is absent from the region today as a result of human activities. The core covers the period from *c.* 11,000 to 2800 cal. yr BP.

Site description

Kagaðarhóll palaeolake (KAGA; 65°35′16″ N, 20°07′58″ W, 114 m a.s.l.) is located south of Húnaflói Bay about 10 km southeast of the village Blönduós in Austur-Húnavatnssýsla County, Northwest Iceland (Figure 1b). Today, the site is a bog but outlines of the palaeolake are visible in aerial photographs, indicating a size of about 4.5 ha. The bog vegetation is dominated by Cyperaceae spp., especially *Eriphorum angustifolium*. The herb *Cardamine nymanii* is common, as are the dwarf shrubs *Betula nana, Salix phylicifolia* and *Salix lanata*. At present the site is surrounded by farmland consisting of hayfields, *Betula nana*–dominated dwarf-shrub heath and eroded gravelly hills. Observations from weather stations are available from Blönduós (from the years 1961 to 1965 and 1981 to 1990; Figure 1b) and from Hjaltabakki at 2.3 km distance from Blönduós (from 1967 to 1981; Figure 1b). The combined mean 1961–1990 tritherm summer temperature from both stations is *c.* 8.7°C, the mean July temperature is *c.* 9.4°C and the mean January temperature is *c.* −2.5°C. The mean annual precipitation is *c.* 458 mm per year (Icelandic Met Office, 2014). At present, there is no record of natural birch woodland in Austur-Húnavatnssýsla County, despite the fact that the mean minimum tritherm temperature is well above the temperature limit for tree growth in Iceland (Jónsson, 2005; Wöll, 2008).

The vegetation in the area, as elsewhere in Iceland, has been influenced by human activities since the settlement *c.* AD 870 because of woodcutting and grazing (Guðbergsson, 1996).

It is important to note that a palaeoecological reconstruction has previously been performed using sediments from the same lake (Vasari, 1972, 1973; Vasari and Vasari, 1990; the lake is wrongly referred to therein as Hafratjörn, which is the name of another small lake nearby). The previous study is plagued by issues with the chronology of the core. For example, samples taken for radiocarbon dating close to a tephra layer identified as Hekla 3 yielded an age more than 1000 ^{14}C years too old. Also, the radiocarbon ages, dated in two batches in 1967 and 1973, are not in chronological order. It is therefore likely that the radiocarbon ages from the entire core are too ambiguous to draw conclusions about the timing of birch immigration or other patterns of Holocene vegetation change in the area. The results by Vasari (1972, 1973) and Vasari and Vasari (1990) have, perhaps as a consequence of unreliable age control, been used as evidence for a delay in the arrival of birch in Austur-Húnavatnssýsla compared with locations such as Skagafjörður and Eyjafjörður, further east in North Iceland (Figure 1a; Caseldine et al., 2006; Hallsdóttir, 1995). The reason for selecting the same location for this study is that it provides an ideal baseline for the study of birch woodland dynamics in the area, as it potentially represents one of the best areas in the region with regard to the optimum conditions required for the development of *Betula pubescens* woodland.

Methods

Field methods and stratigraphy

Four series of overlapping sediment cores were retrieved from near the centre of the palaeolake using a Livingstone piston corer with a Bolivia adaptor fitted with 75 mm diameter polycarbonate tubes. The sediments retrieved range from peat at the top of the core to silty gyttja, with minerogenic sediments at the bottom of the core.

A single depth profile was constructed by overlapping the main sequence of cores (KAGA4) with two other sequences (KAGA1 and KAGA3) to ensure continuity in the sediment column and to avoid potentially disturbed sediments at the top of the core segments. This was done by matching tephra layers, patterns in magnetic susceptibility (MS) and stratigraphic changes observed in the overlapping cores (see supplementary material, available online). The resulting sequence was 679 cm long. The cores were x-rayed for identification of tephra layers. MS measurements were performed on the split core segments at 1 cm intervals using a Bartington MS2 meter and Bartington MS2F probe (Dearing, 1994). Organic matter (OM; by loss on ignition) and dry bulk density (DBD) were measured at 1 cm contiguous intervals. OM was measured by subjecting 1.2 cm^3 of sample to 550°C for 5 h (Bengtsson and Enell, 1986) and DBD by dividing the dry weight of a sample with the volume of the wet sample (Brady and Weil, 1996). The sediments analysed for this study are undisturbed lake sediments from 130 cm depth (10 cm above the Hekla 3 tephra layer; Dugmore et al., 1995) to the bottom of the core. Sediments higher in the core sequence were not analysed because of potential reworking as the lake depth decreased and peat formation began.

Pollen and macrofossil analysis

Subsamples for pollen analysis (2 cm^3) were collected at 4–8 cm intervals between 133 and 675 cm depth in the core. Pollen samples were prepared using standard chemical methods of 10% HCl, 10% NaOH and acetolysis (Faegri and Iversen, 1989; Moore et al., 1991), as well as heavy-liquid separation (Björck et al., 1978; Nakagawa et al., 1998) using LST Fastfloat (a sodium heteropolytungstate solution) to remove minerals, tephra shards and organic debris. Two tablets containing spores of *Lycopodium clavatum* were added to each sample (batch number 1031; Stockmarr, 1971) to enable calculations of concentrations of pollen and spores in the samples, and to calculate pollen accumulation rates (PARs; grains cm^{-2} yr^{-1}). The prepared samples were mounted on glass microscope slides in silicone oil of 12,500 cSt viscosity.

A minimum of 300 indigenous terrestrial pollen grains were counted for each sample, except for the three lowermost samples where pollen concentrations were extremely low. Identification of pollen grains and spores was based on Moore et al. (1991) and a pollen-type slide collection at the University of Iceland. Pollen categories and sums followed Hallsdóttir (1987) and Caseldine et al. (2006). Pollen and spore taxonomy followed Bennett (2007), with a few amendments to better reflect the Icelandic flora (Erlendsson, 2007). Percentages of fungal spores were based on the combined terrestrial pollen sum and sum of fungal spores. A record was made of non-triporate *Betula* pollen, high percentages of which are indicative of hybridization between *Betula nana* and *Betula pubescens* (Karlsdóttir et al., 2008). Identification of spores from coprophilous fungi relied on Van Geel et al. (2003).

The sediments were analysed for plant macrofossils at contiguous 5 cm intervals between 350 and 600 cm to establish the timing of *Betula pubescens* colonization of the area. Between 130 and 350 cm, and 600 and 675 cm, samples were analysed at every other 5 cm interval. Sample volume varied between 35 and 50 mL, depending on the material available. The volume of each sample was determined by displacement in water. The samples were washed through a 125 µm sieve, and vascular plant remains were picked out for identification. Identification was based on various references (e.g. Berggren, 1969; Birks, 2007; Cappers et al., 2012; Katz et al., 1965). Comparisons with reference material were made when possible. Concentrations of macrofossils in 50 mL were calculated. *Betula pubescens* Ehrh. (downy birch) and the subspecies *Betula pubescens* Ehrh. ssp. *tortuosa* (mountain birch) grow in Iceland. They are discussed herein as *Betula pubescens* (sensu lato), as the morphological variations in Icelandic birches are large and morphologies of the two may overlap (Anamthawat-Jónsson and Thórsson, 2003; Thórsson et al., 2001). Otherwise, plant taxonomy follows Kristinsson (2010). Pollen and macrofossil diagrams were constructed using TILIA (version 1.7.16) (Grimm, 2011). Pollen assemblages were divided into pollen zones (PZ) with the aid of CONISS.

Core chronology

The chronology for the core (Figure 2) was constructed using a combination of tephrochronology and radiocarbon dating. Tephra layers were identified visually when thick enough and finer layers identified by using x-ray images, spikes in MS and dips in OM measurements. Samples were taken from all suspected tephra layers found in the sediments and washed through a 90 µm sieve. After inspection in a stereomicroscope, the samples judged to consist of primarily pristine volcanic glass shards were mounted on slides, ground, polished and carbon coated. Geochemical analyses of volcanic glass were performed using Hitachi TM3000 SEM equipped with Bruker X-Flash silicon drift detector, using 15 kV beam voltage applied to a surface of 10 × 10 µm. Analyses were recorded with Bruker Espirit analysis software.

The tephrochronology of North Iceland suffers from a lack of dated tephra layers between the Hekla 5 tephra (7050 cal. yr BP; Thorarinsson, 1971) and the Saksunarvatn tephra (10,300 cal. yr BP; Rasmussen et al., 2006). This part of the core (362–620 cm) was systematically sampled every centimetre for macrofossils for dating. A total of nine macrofossil samples were sent for radiocarbon dating (Figure 2, Table 1). Only three samples of terrestrial macrofossils yielded enough material for dating. Because of the scarcity of terrestrial plant macrofossils in the core, six additional samples of aquatic plant remains (*Potamogeton* fruits and leaf fragments) were picked for dating (Table 1), as well as a sample of moss stems from minerogenic material in the lowest part of the core. The decision to opt for aquatic macrofossils over bulk sediment is based on the fact that radiocarbon dates of bulk material from Icelandic lakes are prone to errors and often do not correlate well with dated tephra layers (Caseldine et al., 2006). The reason for this discrepancy is probably erosion-derived soil organic carbon (cf. Gathorne-Hardy et al., 2009). Lakes in Iceland are devoid of inorganic carbon, and the lake is remote from geothermal activity, thus free of issues concerning these factors (e.g. Ascough et al., 2007; Axford et al., 2007). The radiocarbon dates were calibrated to calendar years BP using IntCal13 (Reimer et al., 2013) in OxCal version 4.2.2 (Bronk Ramsey and Lee, 2013). A smooth-spline model (Figure 2) was constructed in R using the package Clam (Blaauw, 2010).

The age depth model for the core (Figure 2) is based on the previously dated tephra layers (Appendix 1) Hekla 3 (3000 cal. yr BP), Hekla 4 (4200 cal. yr BP; Dugmore et al., 1995), Hekla Ö (6060 cal. yr BP; Gudmundsdóttir et al., 2011), Hekla 5 (7050 cal. yr BP; Thorarinsson, 1971) and Saksunarvatn (10,300 cal. yr BP; Rasmussen et al., 2006). The above tephra layers, except for the Hekla-Ö tephra, have a long and extensive record in North Iceland and the North Iceland Shelf and serve as regional marker horizons (Gudmundsdóttir et al., 2012, and references therein). One tephra layer not previously reported is used in the age depth model (S-layer; Table 1; Appendix 1). We have observed this tephra layer in numerous peat sequences in Austur-Húnavatnssýsla and in three lake cores. Located between the Hekla-Ö tephra (Gudmundsdóttir et al., 2011) and the Hekla 5 tephra (Thorarinsson, 1971), this layer forms a distinct, dark and relatively coarse-grained stratum in organic sequences in the area. Its geochemical fingerprint is that of the Katla volcanic system (Appendix 1). One *Betula* spp. twig and one *Salix* spp. twig situated in direct contact with the tephra were extracted for radiocarbon dating from a peat sequence at the farm Stóra-Búrfell (Figure 1b; core BUR), about 4.5 km from Kagaðarhóll. The results of the two analyses provide dates of 6679–6529 and 6661–6501 cal. yr BP (Table 1), and these are fitted into the age–depth model for KAGA where the tephra was identified at 319 320 cm depth. The time frame of the Saksunarvatn tephra has not yet been established nor whether it is the product of several eruptions (Jennings et al., 2014). The layer is therefore handled as a single event in the age–depth model.

In addition to the dated tephra layers, six of the nine radiocarbon dates analysed complete the age depth model. Two radiocarbon dates were rejected on the basis that they were too old. A *Salix* leaf fragment from right above the Saksunarvatn layer at 618 cm depth yielded an age of 10,425 ± 131 cal. yr BP, thus older than the tephra upon which it rests. A sample of *Potamogeton* leaf fragments from 430 cm depth gave an age that was too old and implies a sedimentation rate too high, considering no changes are seen in sediment characteristics based on the MS and DBD data. The third excluded ^{14}C date, derived from a terrestrial macrofossil sample at 461 cm depth, yielded very little material for dating and was analysed as gas. Because of the large margin of error on the calibrated date, a sample of *Potamogeton* leaf fragments from the same depth was used in the age–depth model instead as it falls within the error of the terrestrial macrofossil sample, and is in sequence with other samples based on *Potamogeton* macrofossils between 461 cm and the Saksunarvatn tephra. Ages are given in calibrated years before present (cal. yr BP; with present assigned to AD 1950).

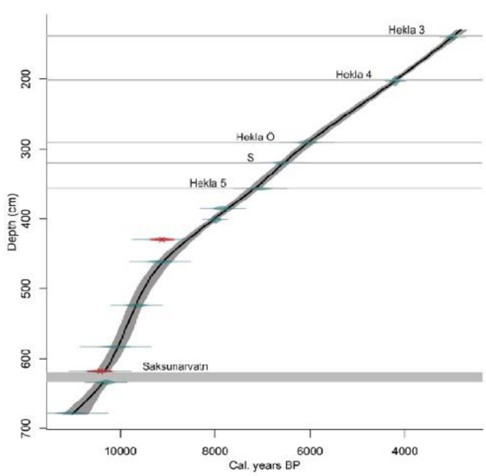

Figure 2. Age–depth model for the Lake Kagaðarhóll core. Horizontal lines indicate depths of tephra layers included in the age-depth model.

Table 1. Radiocarbon dates from the Lake Kagaðarhóll core.

Lab code	Depth (cm)	^{14}C date	Error	$\delta^{13}C$	Average Calendar age	Range (cal. yr BP) 2σ error	Weight (mg)	Material
ETH-56125	385	7003	36	−20.6	7841 ± 95	7936–7746	0.83	*Potamogeton* leaf fragments
ETH-56126	401	7170	35	−35.0	7989 ± 53	8041–7936	0.34	*Empetrum nigrum* and *Betula pubescens* remains
ETH-56127	430	8128	37	−16.8	9120 ± 123	9242–8997	1.00	*Potamogeton* leaf fragments
ETH-56135	461	8209	38	−19.1	9159 ± 128	9286–9031	0.94	*Potamogeton* leaf fragments
ETH-56128[a]	461	8132	89	−30.8	9086 ± 315	9401–8771	N/A	Miscellaneous *Betula pubescens* macrofossils
ETH-56129	524	8695	38	−11.7	9655 ± 109	9764–9546	0.99	*Potamogeton* fruits and leaf fragments
ETH-56130	583	8997	39	−11	10,092 ± 150	10,242–9942	1.00	*Potamogeton* fruits and leaf fragments
SUERC-47862	618	9258	35	−25[b]	10,425 ± 131	10,556–10,294	1.00	*Salix* sp. leaf fragment
SUERC-49702	677	9695	30	−29.1	11,048 ± 158	11,206–10,890	4.50	Moss stems
SUERC-47863[c]	320	5814	30	−27.8	6604 ± 75	6679–6529	32.40	Twig, *Salix* sp.
SUERC-47864[c]	320	5788	30	−30.8	6581 ± 80	6661–6501	18.70	Twig, *Betula* sp.

[a]Measured directly from CO_2 gas.
[b]Assumed.
[c]Dated from peat section BUR.

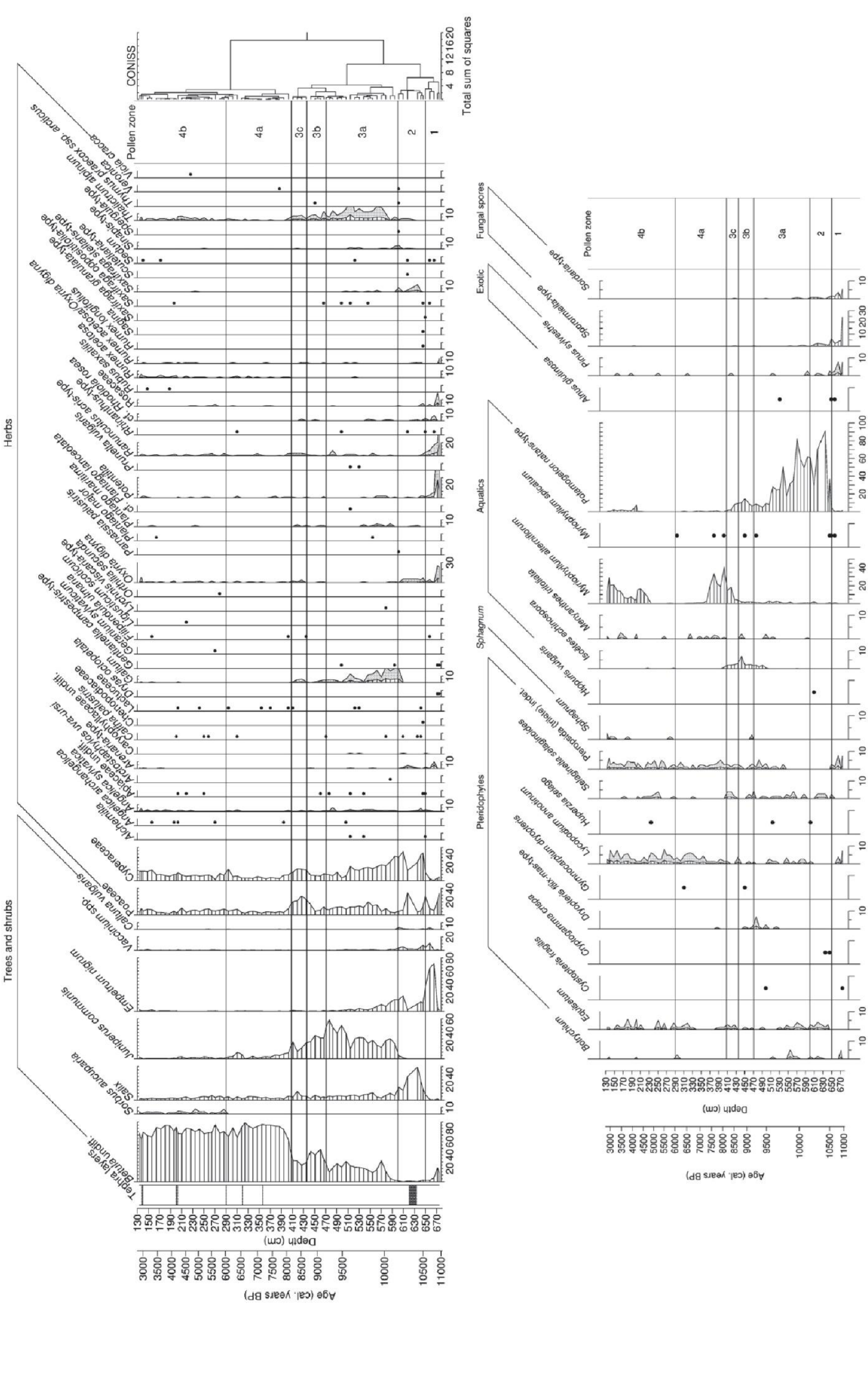

Figure 3. Pollen percentage diagram from Lake Kagaðarhóll. Exaggeration curves of factor 4. Dots signify percentages below 1%. The lithology column shows dated tephra layers used in the age-depth model.

Results

PZ 1 (c. 11,000–10,600 cal. yr BP; 680–650 cm)

Initially, the pollen assemblage (Figure 3) is characterized by a relatively high percentage of Poaceae (grass family) and pioneer taxa such as *Oxyria digyna* and *Arenaria*-type, and herbs such as *Potentilla*-type and *Ranunculus acris*–type. Occasional occurrences of *Dryas octopetala* and *Sedum*-type pollen are recorded in the lowest samples. *Betula* pollen percentages are relatively high in the two lowest samples. By *c.* 10,800 cal. yr BP, there is a peak in *Empetrum nigrum* pollen. *Vaccinium*-type pollen are found in small numbers from *c.* 10,700 cal. yr BP, as well occasional as *Calluna vulgaris* pollen. PARs (grains $cm^{-2}yr^{-1}$) (Figure 4) are very low, with a total PAR of less than 100 grains $cm^{-2}yr^{-1}$ during this period. Exotic pollen from *Pinus* and *Alnus* are recorded in the lowest samples. Spores from the coprophilous (dung-loving) fungi *Sporormiella*-type and *Sordaria*-type are found within this PZ (Figure 3). The few terrestrial macrofossils found (*Empetrum nigrum, Juncus* spp., *Luzula* spp., *Lycopodium annotinum* and *Selaginella selaginoides*) (Figure 5) compare well with the pollen assemblages. MS values are high within the zone, and DBD values decrease from *c.* 1.5 to 0.45 $g\,cm^{-3}$ at the top of the zone accompanied by low OM percentages between *c.* 0.5% at the bottom of the zone, increasing to *c.* 9% at the top of the zone (Figure 6).

PZ 2 (10,600–10,200 cal. yr BP; 650–600 cm)

Cyperaceae and *Salix* pollen increase in both relative and absolute numbers by *c.* 10,600 cal. yr BP (Figures 3 and 4). Although *Empetrum nigrum* pollen decreases after *c.* 10,600 cal. yr BP (Figure 3), the macrofossil record supports its continued presence with seeds and leaves (Figure 5). Pollen from pioneer herb taxa identified in PZ 1, *Oxyria digyna, Arenaria*-type, *Potentilla*-type and *Ranunculus acris*–type, decrease within this zone. There is a progressive decline in minerogenic content, apparent via decreasing MS values and lower DBD from *c.* 0.45 to 0.20 $g\,cm^{-3}$. This is accompanied by an increase in OM deposition from *c.* 9% to 24% (Figure 6). A single *Betula nana* leaf is found at *c.* 10,500 cal. yr BP (Figure 5), and *Betula* pollen values are at *c.* 1–2% for this period (Figure 3).

The environment is disrupted by the deposition of the Saksunarvatn tephra, dated to *c.* 10,300 cal. yr BP (Rasmussen et al., 2006). The layer is marked by OM percentages close to zero and a steep increase in MS and DBD (Figure 6). The pollen assemblage immediately above the layer (617 cm) shows an increase in Poaceae, a relative decrease in *Empetrum nigrum* and Cyperaceae and some decrease in *Salix* pollen compared with the assemblages below the layer. Further above the tephra layer (609 cm), the pollen assemblage recovers to values similar to before its deposition, characterized by Cyperaceae, *Empetrum nigrum, Salix* and Ericales (Figures 3 and 4). A comparable assemblage is reflected in the macrofossil record with remains of *Empetrum nigrum, Salix, Selaginella selaginoides* and *Carex* (Figure 5). Fungal spores of *Sporormiella*-type and *Sordaria*-type occur regularly (Figure 3). Minerogenic inputs decline to pre-Saksunarvatn levels after *c.* 100 years according to the MS and DBD records (Figure 6).

PZ 3a (c. 10,200–9200 cal. yr BP; 600–470 cm)

Juniperus communis pollen appear in the record by *c.* 10,200 cal. yr BP and quickly increase to >30% and PARs > 700 grains $cm^{-2}yr^{-1}$ by 10,100 cal. yr BP. *Betula* pollen increase rapidly to *c.* 20–30% by *c.* 10,000 cal. yr BP, an increase in *Betula* PAR from 14 grains $cm^{-2}yr^{-1}$ at the beginning of the zone to a peak of >1000 grains $cm^{-2}yr^{-1}$ between *c.* 9600 and 9400 cal. yr BP. *Juniperus communis* pollen increase to a peak of *c.* 40–60% between *c.* 9600 and 9200 cal. yr BP, with PARs of 1330–3070 grains $cm^{-2}yr^{-1}$ (Figures 3 and 6). As these taxa become more abundant in the record, values of dwarf shrubs decrease, with a steady decrease in *Empetrum nigrum* pollen, especially after *c.* 9900 cal. yr BP, while *Salix* pollen remain at about 5–10% (Figure 3). This shift is also reflected in the macrofossil record where *Betula nana* fruits and catkin scales are relatively abundant in an otherwise limited record, and occasional *Empetrum nigrum* and *Salix* macrofossils are still found. One *Juniperus communis* macrofossil is recorded, a needle deposited at the same time as the peak in *Juniperus communis* PAR at *c.* 9300 cal. yr BP (Figure 5). One *Betula pubescens* fruit is found at *c.* 9600 cal. yr BP, but *Betula pubescens* catkin scales and fruits sustain a continuous record from *c.* 9300 cal. yr BP (Figures 5 and 6). Additionally, degraded *Betula* fruits that could not be identified to species level were found after *c.* 9600 cal. yr BP (Figure 5). *Sporormiella*-type and *Sordaria*-type spores decrease and almost disappear after *c.* 9000 cal. yr BP. *Potamogeton* pollen are very abundant within this zone but decrease abruptly at *c.* 9600 cal. yr BP (Figure 3) when *Potamogeton natans* fruits, that are abundant in the lower half of the zone, disappear. *Potamogeton perfoliatus* fruits are found in the record after *c.* 9500 cal. yr BP (Figure 5). Large fluctuations in MS and DBD values occur during this period. Spikes in MS occur between 9800 and 9300 cal. yr BP, accompanied by fluctuations in DBD between 0.17 and 0.34 $g\,cm^{-3}$ with sand lenses observed in the sediments between 9700 and 9500 cal. yr BP (Figure 6). Total terrestrial PAR reaches its highest levels in the core within PZ 3a, with values of 4500–6100 grains $cm^{-2}yr^{-1}$ between *c.* 9500 and 9300 cal. yr BP. The main contributor to the increase in total PAR is *Juniperus communis*. The proportion of non-triporate *Betula* pollen during this period ranges between 2% and 9% (Figure 6).

PZ 3b (c. 9200–8700 cal. yr BP; 470–436 cm)

Betula pollen percentages are >30% after *c.* 9200 cal. yr BP (Figure 3). This is accompanied by a decrease in *Juniperus communis* pollen (Figures 3 and 4). The total PAR values decrease mainly because of a drop in *Juniperus communis* PAR from 1460 grains $cm^{-2}yr^{-1}$ at the bottom of the zone to 350 grains $cm^{-2}yr^{-1}$ at the top. *Betula* PAR values measure between 600 and 1000 grains $cm^{-2}yr^{-1}$ within this zone (Figures 4 and 6). PARs of Poaceae, Cyperaceae, *Empetrum nigrum* and herbs such as *Thalictrum alpinum* and *Galium* decrease (Figure 4). Ericales pollen disappear within this zone. *Betula pubescens* macrofossils are recorded continuously during this period (Figures 5 and 6). MS and DBD values are much lower and less variable than before, with DBD between 0.13 and 0.19 $g\,cm^{-3}$ accompanied by elevated OM values between 29% and 43% (Figure 6).

PZ 3c (c. 8700–8200 cal. yr BP; 436–408 cm)

At *c.* 8700 cal. yr BP, *Betula* percentages drop to *c.* 25–30% (Figure 3), accompanied by *Betula* PAR drop to between *c.* 160 and 260 grains $cm^{-2}yr^{-1}$ (Figures 4 and 6). Herbaceous taxa, such as Poaceae and Cyperaceae, increase (Figure 4). The decrease in *Betula* pollen spans about 500 years, over which period *Betula pubescens* macrofossils almost disappear from the record. Only a few macrofossils of *Empetrum nigrum* and *Selaginella selaginoides* are recorded during this period (Figure 5). The total PAR is extremely low, at levels similar to the early Holocene (Figure 6). OM deposition is relatively high at *c.* 34–48%. An unidentified tephra layer is seen in the MS, OM and DBD records at *c.* 8550 cal. yr BP (Figure 6), otherwise values for MS and DBD remain relatively stable within this zone, and DBD values decrease upwards from *c.* 0.12 to 0.14 before *c.* 8400 cal. yr BP and *c.* 0.08 to 0.10 $g\,cm^{-3}$ between *c.* 8400 and 8200 cal. yr BP.

PZ 4a (c. 8200–6000 cal. yr BP; 408–290 cm)

Betula pubescens macrofossils establish a continuous presence from *c.* 8200 cal. yr BP and by *c.* 7900 cal. yr BP *Betula* pollen

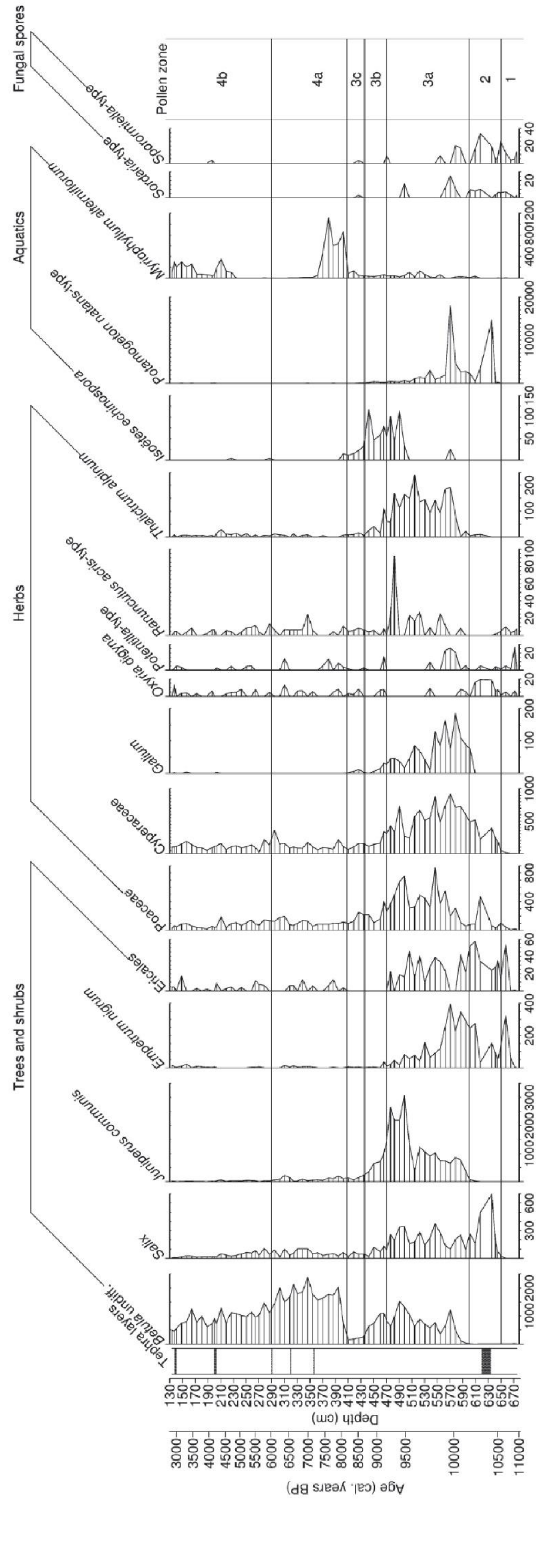

Figure 4. Pollen accumulation rate (PAR, grains cm^{-2} yr^{-1}) from Lake Kagaðarhóll for selected taxa.

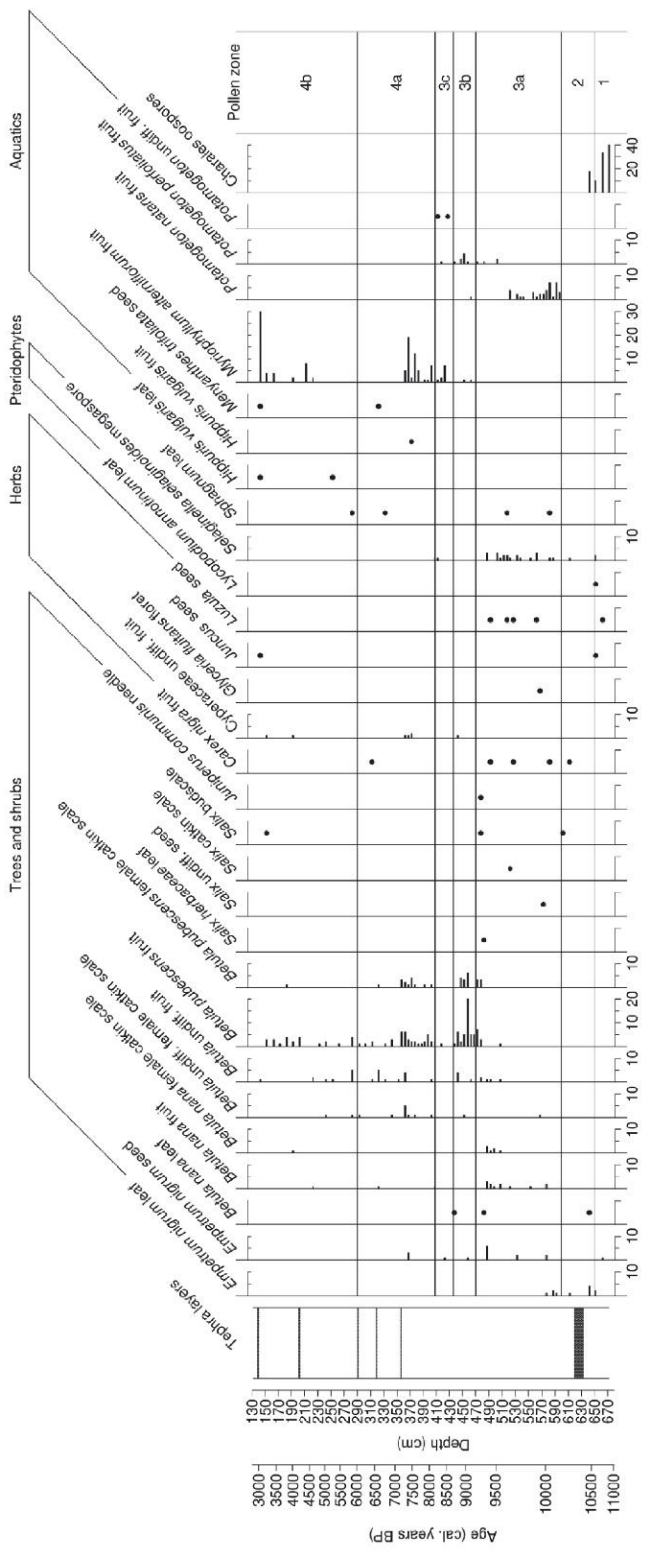

Figure 5. Plant macrofossil diagram from Lake Kagaðarhóll. Concentrations in 50 mL of sediment.

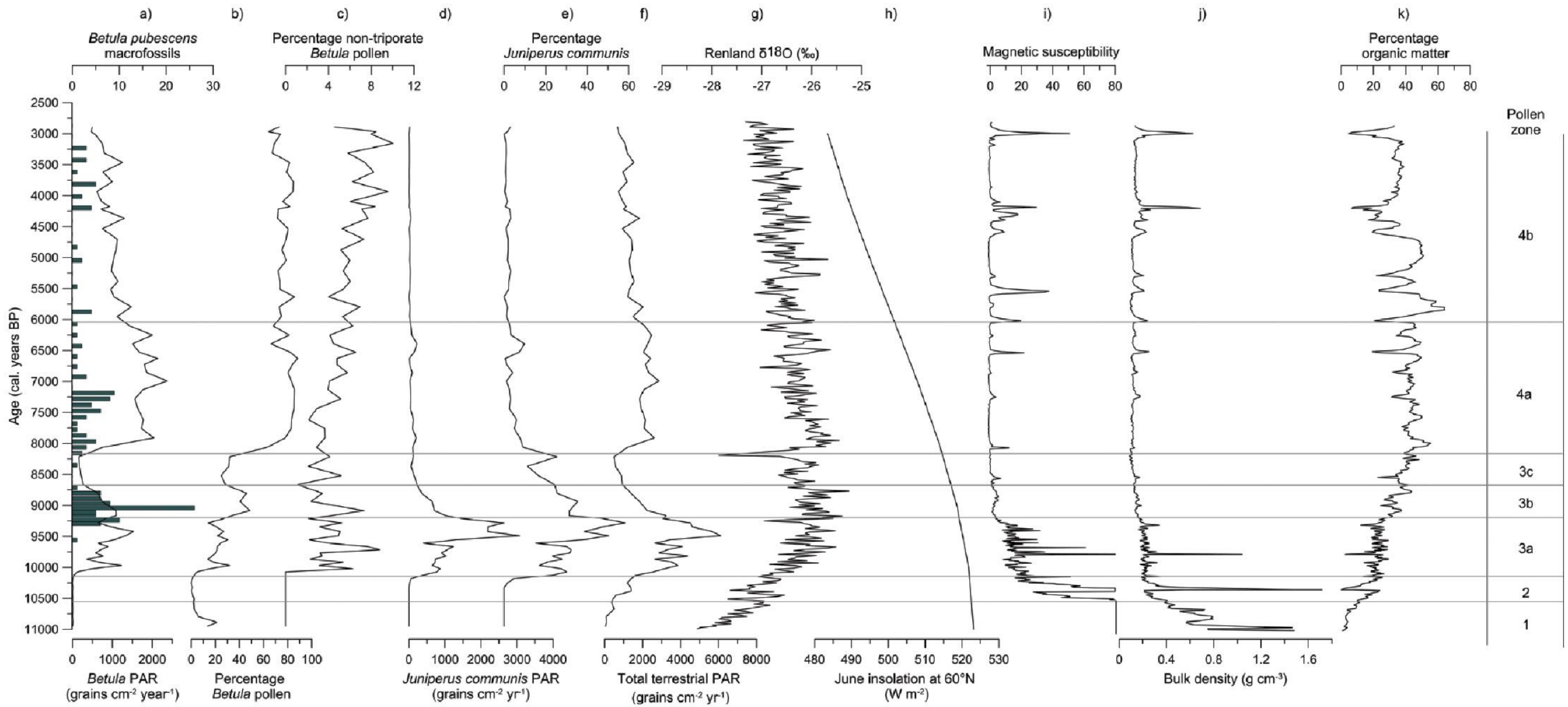

Figure 6. Summary diagram for Lake Kagaðarhóll showing (a) *Betula* pollen accumulation rate (PAR) (line) and *Betula pubescens* macrofossil occurrence in 50 mL of sediment (bars); (b) percentage of *Betula* pollen; (c) percentage of non-triporate *Betula* pollen; (d) *Juniperus communis* PAR; (e) percentage *Juniperus communis* pollen; (f) total terrestrial PAR; (g) Renland ice-core $\delta^{18}O$ record, 20-year average uplift corrected (Vinther et al., 2009); (h) June insolation at 60°N (Berger and Loutre, 1991); (i) magnetic susceptibility (MS; showing arbitrary values below 80); (j) dry bulk density (DBD); and (k) organic matter (OM; measured by loss on ignition).

percentages reach *c.* 80% (Figure 3), with PAR values between *c.* 1500 and 2000 grains cm^{-2}yr^{-1} (Figures 4 and 6). As *Betula* pollen increase, *Juniperus communis* pollen become less abundant. There is also a relative decrease in herbaceous taxa such as Cyperaceae, Poaceae, *Thalictrum alpinum* and *Galium* (Figures 3 and 4). The presence of *Betula pubescens* is confirmed by the occurrences of its macrofossils throughout this period (Figures 5 and 6). Values of MS and DBD remain low and stable (apart from where tephra layers are present in the sediment) with DBD between *c.* 0.11 and 0.14 gcm^{-3}. OM values are relatively high, between *c.* 34% and 55% (Figure 6).

PZ 4b (c. 6000–3000 cal. yr BP; 290–130 cm)

Gradually declining *Betula* PAR values fall below 1500 cm^{-2}yr^{-1} after *c.* 6000 cal. yr BP (Figures 4 and 6). This decline is not seen clearly in the pollen percentages, where there is only a slight drop in *Betula* at *c.* 6400 cal. yr BP when values become more variable than in PZ 4a (Figures 3 and 6). *Betula pubescens* macrofossils are found within this zone although in smaller numbers than in PZ 3a (Figure 5). *Sorbus aucuparia* pollen appear for the first time in the record around 6000 cal. yr BP (Figure 3).

Variations in OM, MS and DBD increase during this period. After the deposition of the Hekla 4 tephra layer at *c.* 4200 cal. yr BP (Dugmore et al., 1995), DBD is about 0.12–0.18 gcm^{-3} and OM is *c.* 30–38% after *c.* 4000 cal. yr BP (Figure 6). *Betula* PAR decreases to less than 1000 grains cm^{-2}yr^{-1} after 4200 cal. yr BP (Figures 4 and 6). Percentages of non-triporate pollen increase steadily from *c.* 7300 cal. yr BP, reaching the highest values in the record of 6–10% after *c.* 4200 cal. yr BP (Figure 6).

Holocene vegetation and climate dynamics at Lake Kagaðarhóll

Early plant succession in a recently deglaciated environment

The Kagaðarhóll record extends back to *c.* 11,000 cal. yr BP. The pollen assemblages in the lowermost samples represent denuded, recently deglaciated landscape (Figure 3). Pollen from the pioneer taxon *Oxyria digyna* is prominent in the early assemblage. Pollen from plants that grow on gravel flats (Kristinsson, 2010) are found in the assemblages, for example, *Ranunculus acris* type (which may originate from *Ranunculus glacialis*), as well as *Dryas octopetala*. *Potentilla*-type pollen that likely represent *Sibbaldia procumbens*, a plant typical of areas with heavy snow cover, are also prominent in the early assemblages. *Arenaria*-type and *Sedum*-type pollen likely represent taxa such as *Arenaria norvegica, Sedum acre* and *Sedum annuum* which have been found on moraines in front of the retreating glacier Skaftafellsjökull in Southeast Iceland (Persson, 1964). Low local pollen production from the sparse vegetation is evident from the low total PAR during the pioneer vegetation phase (Figure 6). The pollen record indicates rapid vegetation changes around Lake Kagaðarhóll during the earliest part of the Holocene. By *c.* 10,800 cal. yr BP, there is a short-term shift towards *Empetrum nigrum*–dominated vegetation (Figure 3) with a transition to dwarf-shrub heath at *c.* 10,600 cal. yr BP, as values for *Salix* and Cyperaceae pollen increase (Figures 3 and 4) and *Calluna vulgaris* pollen appear (Figure 3). Although it is difficult to infer vegetation cover from pollen data, the pollen assemblages compare favourably with present flora on moraines in front of Skaftafellsjökull, Southeast Iceland, where *Empetrum nigrum* and *Calluna vulgaris* dwarf shrubs with interspersed *Salix lanata* and *Salix phylicifolia* shrubs are prominent. Today, these species, along with mosses, account for *c.* 61% vegetation cover on 65-year-old moraines, and *c.* 67% on 120-year-old moraines (Vilmundardóttir et al., 2015). Therefore, vegetation around Lake Kagaðarhóll may have reached *c.* 60% cover by *c.* 10,300 cal. yr BP. Dwarf shrubs and herbaceous vegetation (predominantly Cyperaceae) around Lake Kagaðarhóll is similar to other vegetation reconstructions pre-dating the Saksunarvatn tephra at Tröllaskagi peninsula (Caseldine et al., 2006) and Skagi peninsula (Rundgren, 1998), North Iceland.

Specific plants may serve as temperature indicators during the earliest period of the Holocene. Indicator species found in the early-Holocene record at Lake Kagaðarhóll such as *Selaginella selaginoides* and *Calluna vulgaris* grow at a minimum July temperature of 7°C and *Empetrum nigrum* at 7.7°C (Kolstrup, 1979, 1980). Therefore, relatively warm summers in the area around the lake during the early Holocene may be proposed. This is in accordance with generally warm ocean conditions seen in various sediment data from the North Iceland Shelf where optimum thermal conditions were recorded from *c.* 10,000 cal. yr BP (e.g. Andrews and Giraudeau, 2003; Castañeda et al., 2004; Justwan et al., 2008; Knudsen et al., 2004; Rousse et al., 2006). Early-Holocene warmth is also reflected in chironomid-inferred mean July temperature (CI-T) at Tröllaskagi peninsula where July temperatures had likely reached 7°C before the deposition of the Saksunarvatn tephra (Caseldine et al., 2006). This may, however, be an underestimate of actual mean July temperatures at Tröllaskagi, as late arrival of thermophilous chironomid species during the early Holocene may skew the assemblages, and therefore the temperature reconstruction (Axford et al., 2007; Caseldine et al., 2003).

Impact of tephra deposition and aeolian processes on the terrestrial environment during the early Holocene

High fluxes of material transported by aeolian processes following deglaciation and tephra deposition from the Saksunarvatn event may have influenced the vegetation succession around Lake Kagaðarhóll as temperatures rose. The frequent recording of the Saksunarvatn tephra, often at great thickness (>10 cm) in Iceland (e.g. Caseldine et al., 2003, 2006; Larsen et al., 2012; Striberger et al., 2012; Stötter et al., 1999; Wastl et al., 2001), allows for the inference that it affected landscape stability and perhaps vegetation succession. Abrasion by wind erosion as well as burial by aeolian material may cause severe damage to vegetation (Gisladottir et al., 2005). The pollen assemblage 3 cm above the Saksunarvatn tephra indicates burial by material of thickness in excess of 10 cm. PARs and percentages of *Empetrum nigrum* and Cyperaceae decrease following the event, and these taxa have been shown to have an inverse relationship with sand thickness (Vilmundardóttir et al., 2009). Meanwhile the increase in Poaceae (Figure 4) may represent an increase in the species *Festuca richardsonii* which has a positive relationship with sand burial, with an increase in the taxon with sand thickness in excess of 10 cm (Vilmundardóttir et al., 2009). Higher above (11 cm) the Saksunarvatn tephra layer, the pollen assemblages regain similarities to those before its deposition, probably representing the re-establishment of a dwarf shrub dominated environment. The relatively fast recovery of vegetation to pre-deposition levels within about 100 years is in accordance with previous results from Skagi peninsula (Rundgren, 1998) and Tröllaskagi peninsula (Caseldine et al., 2006) where deposition of the Saksunarvatn tephra did not have a radical or permanent impact on vegetation development (Figure 1a). A gradual trend of stabilization over several centuries followed, with material left behind by retreating glaciers (Larsen et al., 2012; Striberger et al., 2012) and residual tephra being contained by expanding and developing vegetation.

The recording of spores from the coprophilous fungi *Sporormiella*-type and *Sordaria*-type (Figures 3 and 4) is of some interest. Coprophilous fungi are more or less reliant upon herbivores for spore germination (e.g. Cugny et al., 2010).

Given the absence of mammal herbivores in pre-settlement Iceland, the presence of these spores may indicate the migration of birds into the post-glacial landscapes of Iceland. *Sporormiella* spp. and *Sordaria* spp. have been found on modern rock ptarmigan (*Lagopus muta*) faeces and that of other bird species in Iceland (Hallgrímsson and Eyjólfsdóttir, 2004).

Environmental instability, local increase in Juniperus communis and regional expansion of Betula pubescens

Change from open fell-field and tundra vegetation towards taller, more layered shrub vegetation occurs with a shift towards *Juniperus communis–Betula nana–Salix* shrub heath at *c*. 10,100 cal. yr BP. Between 9600 and 9200 cal. yr BP, there is a pronounced *Juniperus communis* pollen peak, with PARs up to 3070 grains $cm^{-2} yr^{-1}$ (Figures 3, 4 and 6). The near absence of *Juniperus communis* macrofossils from the record is not unexpected and is probably because of the combination of lack of inflow into the lake and the relatively high weight of needles and cones preventing transport to the coring site, which is at a distance of >100 m from the shore (cf. Birks and Bjune, 2010; Dieffenbacher-Krall, 2007).

A *Juniperus communis* phase similar to the one at Lake Kagaðarhóll can be seen at other sites in North (Caseldine et al., 2006; Hallsdóttir, 1995; Rundgren, 1998) and Northwest (Caseldine et al., 2003) Iceland (Figure 1a). Although *Juniperus communis* produces large quantities of pollen, they are poorly represented in sediments and even low percentages of pollen are commonly inferred to represent a strong presence of the plant in the vicinity of sampling locations (Huntley and Birks, 1983; Schofield et al., 2007). High percentages and PARs such as those recorded after *c*. 10,100 cal. yr BP at Lake Kagaðarhóll can only be produced by an upright growth form of dense *Juniperus communis* scrub (Birks, 1973). Taller growth form of *Juniperus communis* indicates relatively high mean July temperature, perhaps above 10°C (Kolstrup, 1980). The presence of *Myriophyllum alterniflorum* in the pollen record (Figures 3 and 4) also indicates relatively high mean July temperatures, as high as *c*. 10°C (Kolstrup, 1980). The peak in *Juniperus communis* coincides with a shift from *Potamogeton natans* to *Potamogeton perfoliatus* (Figure 5) which requires relatively warm lake conditions during summers (Kristinsson, 2010). The high total PAR values, because of the substantial deposition of *Betula* and *Juniperus communis* pollen, may indicate an optimum period for pollen production for both taxa (Figure 6). This may be an indication of warm Holocene conditions in Iceland already by *c*. 10,100 cal. yr BP. Warm summers during the early Holocene at Lake Kagaðarhóll are in accordance with recorded warm conditions during the early Holocene in the ocean north of Iceland (e.g. Castañeda et al., 2004; Justwan et al., 2008; Knudsen et al., 2004; Rousse et al., 2006), and oxygen isotope values from the Renland ice-core record show a period of low $\delta^{18}O$ values at this time (Vinther et al., 2009; Figure 6). This trend follows maximum solar insolation during the early Holocene (Berger and Loutre, 1991; Figure 6). Glaciers in the Icelandic highlands were probably smaller than today during the early Holocene. Larsen et al. (2012) have argued that Langjökull in the western highland was smaller than today when the Saksunarvatn tephra was deposited and Eyjabakkajökull in the eastern highlands had retreated behind its current position by 9300 cal. yr BP (Striberger et al., 2012). This is in agreement with chironomid-inferred mean July temperatures from Eyjafjörður, which also indicate that early-Holocene temperatures may have been warmer than today (Langdon et al., 2010).

The environment was still relatively unstable, indicated by the high minerogenic input to the lake seen in the OM, MS and DBD data (Figure 6). *Juniperus communis* is highly competitive in disturbed environs and on nutrient poor soils (García et al., 2000), but the species' intolerance to shade (Thomas et al., 2007a) would have put it at a disadvantage as taller birch trees formed an increasingly closed canopy. The apparent delayed arrival of *Betula pubescens* to Lake Kagaðarhóll despite rising temperatures is likely because of limiting factors such as soil properties, or distance from seed source. Well-drained sandy soils may have given drought-tolerant *Juniperus communis* (Thomas et al., 2007a) an advantage over drought-intolerant *Betula pubescens* (Atkinson, 1992). The succession from *Juniperus communis* to *Betula pubescens* is similar to that seen in Europe during the Late Glacial, where the spread of *Betula pubescens* may have been hindered by factors other than temperature, such as soil moisture (Birks and Birks, 2014; Mortensen et al., 2014).

In the absence of Icelandic PAR references, the *Betula* PAR values may be compared with published modern *Betula* PAR values from Scandinavia. *Betula* PARs of >500 grains $cm^{-2} yr^{-1}$ from *c*. 10,000 cal. yr BP at Lake Kagaðarhóll might be interpreted as sparse presence of *Betula pubescens* around the lake, with *Betula* PAR of >1000 grains $cm^{-2} yr^{-1}$ indicating open forest (Hicks, 2001) established between *c*. 9550 and 9400 cal. yr BP (Figures 4 and 6). However, only one *Betula pubescens* fruit was found at *c*. 9550 cal. yr BP (Figure 6), while only *Betula nana* catkin scales were found (Figure 5). Further *Betula* fruits were found between *c*. 9600 and 9300 cal. yr BP, but these were too degraded to be identified to species level. As birch fruits are prominent in modern sediments from sites where birch trees are located (Jackson and Booth, 2007), the lack of macrofossils concurrent with the high *Betula* PARs may represent a regional increase in *Betula pubescens* around 10,000 cal. yr BP and a sporadic occurrence close to the lake until *c*. 9300 cal. yr BP. High occurrence of non-triporate pollen in the sediment provides further evidence for the presence of tree birch in the region. Non-triporate *Betula* pollen are recorded in modern individuals of both *Betula nana* and *Betula pubescens* in Iceland. On average, 2.4% of pollen produced by individuals of *Betula nana* pollen are non-triporate and 0.7% in individuals of *Betula pubescens*. A much higher number, 12.2%, of non-triporate pollen grains occur in hybrid individuals of the two species (Karlsdóttir et al., 2008). High proportion of non-triporate pollen therefore indicates the presence of hybrids and, in turn, the presence of both parent species in the region. The proportion of non-triporate pollen during this period ranges between 2% and 9% (Figure 6), which indicates hybridization already taking place during the early Holocene, similar to what has been observed in other early-Holocene pollen records from Iceland (Karlsdóttir, 2014; Karlsdóttir et al., 2009, 2012).

Establishment of birch woodland around Lake Kagaðarhóll

The first unambiguous evidence for the existence of *Betula pubescens* around the lake is seen at *c*. 9300 cal. yr BP, when macrofossils from the species are present continuously over several centuries (Figures 5 and 6). Further development towards *Betula pubescens* woodland is depicted in the pollen record from *c*. 9200 cal. yr BP, when *Betula* pollen percentages reach above 30%. Between 9100 and 8800 cal. yr BP, *Betula* pollen account for *c*. 45% of land pollen with PARs of 640 up to 1100 grains $cm^{-2} yr^{-1}$ (Figure 3). A simultaneous decrease in *Juniperus communis* may reflect increased competition with *Betula pubescens* as *Juniperus communis* is intolerant of shade (Thomas et al., 2007a). The change towards a closed canopy and woodland ecosystem is also seen from the large decrease in pollen deposition from dwarf shrubs, graminoids and other herbs (Figure 4). Stabilization of the environment coincident with woodland development is reflected in lower and more stable MS values and a rise in OM deposition within the lake (Figure 6). The increase in *Betula pubescens* in the record between *c.* 9300 and 8700 cal. yr BP is indicative of relatively high summer temperatures. This period coincides with a peak in mean July CI-T at Tröllaskagi peninsula between *c.* 9500 and 9000 cal. yr BP (Caseldine et al., 2006). Within this period, *Betula* PAR reaches >1000 grains $cm^{-2} yr^{-1}$ at Kagaðarhóll (Figures 4 and 6), which may indicate open forest according to the Scandinavian model (Hicks, 2001). This initial phase of birch woodland encroachment around the lake lasted for about 500 years.

Terrestrial ecosystem response to cooling at c. 8700 cal. yr BP

At about 8700 cal. yr BP, there is a rapid drop in *Betula* PAR to values of <270 grains $cm^{-2} yr^{-1}$ (Figures 4 and 6). The low PARs indicate a decline in birch pollen deposition to values below the limit of birch presence at (*c.* 250 grains $cm^{-2} yr^{-1}$; cf. Seppä and Hicks, 2006). The proportional increase in Poaceae may indicate expansion of grassland at the same time. The decrease in total PAR (Figure 6) and scarcity of macrofossils deposited (Figure 5) indicate a drop in both pollen and seed production, not only by *Betula pubescens* but also other plants growing around Lake Kagaðarhóll between *c.* 8700 and 8200 cal. yr BP. This likely represents lower spring and summer temperatures, with tritherm temperatures below 7.2°C (cf. Wöll, 2008). This is in accordance with a period of gradual cooling of mean July CI-T temperatures in Tröllaskagi peninsula between *c.* 9000 and 8100 cal. yr BP (Caseldine et al., 2006). Cooler summer conditions are seen in data from both Haukadalsvatn in West Iceland and Hvítárvatn in the highlands (Figure 1a) between *c.* 8650 and 7850 cal. yr BP (Geirsdóttir et al., 2013; Larsen et al., 2012). In Lögurinn, East Iceland (Figure 1a) a cooling takes place later, between *c.* 8200 and 8000 cal. yr BP (Striberger et al., 2012). A minor cooling is observed on the North Icelandic Shelf at *c.* 8200 cal. yr BP (Castañeda et al., 2004; Ran et al., 2006), with a small change in sea surface temperature (SST) (Andersen et al., 2004) but a more pronounced cooling is seen in cores further offshore and to the east (Eiríksson et al., 2000; Knudsen et al., 2004). The cooling seen in several terrestrial proxy records from Iceland demonstrates that the extensive impact on the terrestrial environment in Iceland occurred earlier than the short cold incursion *c.* 8200 cal. yr BP seen in marine data from the North Atlantic (Alley and Ágústsdóttir, 2005; Alley et al., 1997) and several Greenland ice-core records (Thomas et al., 2007b). A possible explanation for the change in vegetation around Lake Kagaðarhóll at this time is the presence of sea-ice. Air temperature in Iceland is correlated with the presence of sea-ice (Bergþórsson, 1969; Ogilvie, 1984, 1992), and an increased occurrence of sea-ice during spring and summer would have been accompanied by lower air temperatures. More frequent occurrences of sea-ice during spring and summer are likely because of episodes of weaker Irminger Current and a stronger sea-ice bearing East Greenland Current on the North Iceland Shelf between *c.* 9000 and 8000 cal. yr BP (Ran et al., 2006). Although most Greenland ice-core records only show a short cold period (Thomas et al., 2007b), the Renland ice-core isotope data show a trend towards higher $\delta^{18}O$ values already at around 8700 cal. yr BP (Vinther et al., 2009; Figure 6). Colder spring and summer temperatures after 8700 cal. yr BP may have drastically hampered pollen and seed production of *Betula pubescens* and other plants. Cold temperatures during spring time have been linked to loss of male catkins in *Betula pubescens*, which in turn leads to low pollen production (Pichugina, 1972). This may be the reason for the low *Betula* pollen accumulation and the absence of fruits and catkin scales from the Lake Kagaðarhóll sediments. *Betula pubescens* trees usually have a short life span of less than 100 years (Gimingham, 1984). However, following damage, the trees can still reproduce by sprouting from basal buds (Kauppi et al., 1987), and mountain birch (*Betula pubescens* Erhr. ssp. *tortuosa*) regenerates mainly from stems (Verwijst, 1988). Therefore, the near absence of *Betula pubescens* from the macrofossil record and the very low *Betula* PAR over several centuries may indicate either a retreat of birch from the area around the lake or a shift towards a period of vegetative reproduction by trees and other plants while conditions were too harsh for sexual reproduction. The Kagaðarhóll record shares similarities with the record from Lake Vatnskotsvatn in Skagafjörður (Figure 1a). There, an initial expansion of *Betula pubescens* was halted at *c.* 8300 cal. yr BP (7500 ^{14}C yr BP) with a regression towards a *Juniperus–Salix–Betula nana* heath. However, birch woodland re-established itself by *c.* 8000 cal. yr BP (7200 ^{14}C yr BP; Hallsdóttir, 1995). A dip in total PAR similar to the one in the Lake Kagaðarhóll record is seen during the *Betula* retreat at Vatnskotsvatn. A similar regression in vegetation development is not seen in records from Eyjafjörður (Figure 1a) to the east of Skagafjörður, where birch persisted uninterrupted (Caseldine et al., 2006). Nor is it seen in data from Efstadalsvatn (Figure 1a) in the Westfjords (Caseldine et al., 2003), where dwarf-shrub/heath vegetation would have been less sensitive to cooling climate than birch woodlands of Austur-Húnavatnssýsla and Skagafjörður. Cooler conditions may have affected vegetation in Northwest Iceland worse than central North Iceland during this period, when sea-ice may have often lingered in Húnaflói and Skagafjörður during spring and early summer.

There are no indications of increased erosion despite the clear impact on birch woodland during this period. In fact, land surface seems to have become more stable, as inferred from the decrease in MS and DBD. This demonstrates the importance of a continuous vegetation cover and the ecological structure of the established woodland to inhibit erosion in the face of inhospitable conditions during this period.

Maximum extent of Holocene birch woodlands

The transition back to birch woodland occurs within a span of 300 years, with *Betula pubescens* macrofossils reappearing by *c.* 8200 cal. yr BP (Figures 5 and 6) followed by a substantial increase in *Betula* pollen from *c.* 7900 cal. yr BP (Figures 3 and 4). *Betula* PAR values representative of forested areas, between 1500 and 2000 grains $cm^{-2} yr^{-1}$, are recorded after *c.* 7900 cal. yr BP (Figures 4 and 6). These *Betula* PAR values indicate a dense forest surrounding the lake according to the classification offered by Hicks (2001). The subsequent decline in *Juniperus communis* is likely because of the establishment of a closed canopy with heavy shade (cf. Thomas et al., 2007a). A similar decrease in herbs, such as graminoids, *Galium* and *Thalictrum alpinum*, is a further indication of a closing canopy (Figures 3 and 4). This dense birch woodland surrounded Lake Kagaðarhóll from *c.* 7900 to 6000 cal. yr BP. At this time, mean July temperatures at Tröllaskagi may have been higher than at present, with warm conditions representing the HTM considered to last from *c.* 8000 to 6700 cal. yr BP (Caseldine et al., 2006). The expansion of birch woodland during the early to mid-Holocene reflects the strong relationship between *Betula pubescens* growth and high summer temperatures. In Tröllaskagi, Wastl et al. (2001) found that *Betula pubescens* was present at elevations between 450 and 500 m a.s.l. between *c.* 7600 and 6800 cal. yr BP. At Vatnskotsvatn, the *Betula* peak occurred between *c.* 8000 and 6800 cal. yr BP (7200 to 6000 ^{14}C yr BP; Hallsdóttir, 1995). In contrast, only a short peak in *Betula pubescens* pollen is seen in pollen data from Þistilfjörður, Northeast Iceland (Figure 1a) at *c.* 7200 cal. yr BP, where maximum Holocene birch woodland extent occurred later, at *c.* 5000 cal. yr BP (Karlsdóttir, 2014). A warm period defined as HTM is observed between *c.* 7850 and 5450 cal. yr BP in Hvítárvatn in the highlands (Larsen et al., 2012) and Haukadalsvatn, West Iceland (Geirsdóttir et al., 2013) and at *c.* 7900 to 7000 cal. yr BP in Lake Lögurinn, East Iceland (Striberger et al., 2012).

Onset of Neoglaciation and harsher environmental conditions

A decline in woodland is seen in the *Betula* PAR data, with values gradually falling to below 1500 grains $cm^{-2} yr^{-1}$ from *c.* 6000 cal. yr BP, indicating open woodland. After *c.* 4200 cal. yr BP, the PAR values fall to below 1000 grains $cm^{-2} yr^{-1}$, indicating a sparse presence of *Betula pubescens* (Figures 4 and 6) (Hicks, 2001). *Sorbus aucuparia* pollen appear after *c.* 6000 cal. yr BP (Figure 3) as the woodland begins to open up. Because of the entomophilous pollination of *Sorbus aucuparia*, it cannot become prominent in a pollen record dominated by the anemophilous *Betula pubescens*. Therefore, the absence of *Sorbus aucuparia* pollen is not necessarily proof of the plants' absence from the Icelandic HTM woodlands (Hallsdóttir, 1995). Although the transition into Neoglaciation is seen from *c.* 6000 cal. yr BP at Lake Kagaðarhóll, birch is still present towards the end of the Lake Kagaðarhóll record at *c.* 2800 cal. yr BP, indicating that summer temperatures were still relatively high.

Increasing environmental instability is seen in the record after the deposition of the Hekla 4 tephra layer *c.* 4200 cal. yr BP (Dugmore et al., 1995). The Hekla 4 tephra is one of the most prominent Holocene tephra layers found in Icelandic sediments, with about 6.7 km^3 of material deposited on land during the eruption (Larsen and Thorarinsson, 1977). An increase in deposition of minerogenic matter after *c.* 4200 cal. yr BP is seen from an increase in DBD (Figure 6). Impact of great tephra deposition and subsequent aeolian processes on vegetation are, however, not reflected in the pollen record. There is no direct indication in the pollen record of plant burial around Lake Kagaðarhóll, such as followed the deposition of the Saksunarvatn tephra. However, the increased occurrence of non-triporate *Betula* pollen after 4200 cal. yr BP may be because of increased hybridization in response to deteriorating environmental conditions, allowing *Betula nana* to invade previously forested areas. The inverse relationship between non-triporate *Betula* pollen percentages and *Betula* PAR values indicates that hybridization may increase as PAR declines because of cooling climate and harsher environmental conditions. Previous studies indicate that hybridization may occur in response to woodland expansions because of warming climate coinciding with increasing *Betula* PARs (Karlsdóttir, 2014; Karlsdóttir et al., 2012).

The timing of the transition to Neoglaciation at Lake Kagaðarhóll is in agreement with other terrestrial records which place the onset of cooling and more unstable conditions from *c.* 5500 to 4200 cal. yr BP (Geirsdóttir et al., 2013; Larsen et al., 2012; Striberger et al., 2012). On the North Iceland Shelf, optimum warmth lasted until 6000–5000 cal. yr BP, when conditions became colder and more variable (e.g. Andresen et al., 2005; Castañeda et al., 2004; Justwan et al., 2008; Knudsen et al., 2004; Ran et al., 2006; Rousse et al., 2006). Increased landscape destabilization after 4200 cal. yr BP at Lake Kagaðarhóll is comparable with other terrestrial proxy records for erosion (Geirsdóttir et al., 2013; Larsen et al., 2012; Striberger et al., 2012). The effects of deteriorating climate at the onset of Neoglaciation are undoubtedly at work here, although the consequences of the great tephra fall at *c.* 4200 cal. yr BP could also be of importance given that the tephra was deposited over ecosystems already under pressure from deteriorating climate. The environmental consequences of, and responses to, the large pre-historic Hekla eruptions (Larsen and Thorarinsson, 1977) are not well known (but see Caseldine and Hatton, 1994).

Conclusion

The Kagaðarhóll record clearly reveals both long- and short-term Holocene climate and environmental change. It highlights the importance of vegetation cover for landscape stability, as both deglaciation and the Saksunarvatn tephra released massive amounts of minerogenic material into the environment. The composition of the vegetation community seems to have quickly recovered to its pre-deposition state following the Saksunarvatn tephra fall. However, aeolian deposits, probably a combination of material left behind by retreating glaciers as well as the tephra, were not constrained as the vegetation cover remained discontinuous and this left its mark on environmental stability and possibly vegetation development for several centuries. The importance of vegetation for environmental stability in preventing erosion because of deteriorating climate conditions is apparent from the data as erosion did not increase in response to the 8700 cal. yr BP cooling.

The reconstruction from Lake Kagaðarhóll shows how environmental instability and warm climate drove early-Holocene vegetation development. High input of *Juniperus communis* pollen into the lake after *c.* 10,100 cal. yr BP and high regional production of *Betula* pollen likely represent high summer temperatures during the early Holocene. Birch woodland was established in Austur-Húnavatnssýsla as early as *c.* 9200 cal. yr BP, much earlier than has previously been thought and at a time comparable with other locations in North Iceland. The record conclusively documents the impact of the cooling seen in various other terrestrial and marine records during the period *c.* 8700–7900 cal. yr BP on vegetation. The severe decrease in plant reproduction indicates a period of decreased spring and summer temperatures, possibly because of increased occurrences of sea-ice carried by a stronger East Greenland Current. The reconstruction from Lake Kagaðarhóll emphasizes the potential for palaeoecological reconstructions from Iceland to be used as an indicator of climate and environmental change, not only in Iceland but also in the North Atlantic. In addition, the emphatic response of birch around Lake Kagaðarhóll to the cooling at 8700 cal. yr BP and Neoglaciation shows the potential of the taxon to record signals of climate and environmental change. The Lake Kagaðarhóll record demonstrates that macrofossils are an important addition to a robust pollen dataset and a combined record of pollen percentages, pollen PARs, macrofossils and other proxies can provide a thorough reconstruction of vegetation dynamics environmental stability and climate change in Iceland.

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References

Alley RB and Ágústsdóttir AM (2005) The 8k event: Cause and consequences of a major Holocene abrupt climate change. *Quaternary Science Reviews* 24: 1123–1149.

Alley RB, Mayewski PA, Sowers T et al. (1997) Holocene climatic instability: A prominent, widespread event 8200 yr ago. *Geology* 25: 483–486.

Anamthawat-Jónsson K and Thórsson AT (2003) Natural hybridisation in birch: Triploid hybrids between Betula nana and *B. pubescens*. *Plant Cell, Tissue and Organ Culture* 75: 99–107.

Andersen C, Koç N and Moros M (2004) A highly unstable Holocene climate in the subpolar North Atlantic: Evidence from diatoms. *Quaternary Science Reviews* 23: 2155 2166.

Andresen CS, Bond G, Kuijpers A et al. (2005) Holocene climate variability at multidecadal time scales detected by sedimentological indicators in a shelf core NW off Iceland. *Marine Geology* 214: 323 338.

Andresen CS, Hansen MJ, Seidenkrantz MS et al. (2013) Mid-to-late-Holocene oceanographic variability on the Southeast Greenland shelf. *The Holocene* 23: 167–178.

Andrews JT and Giraudeau J (2003) Multi-proxy records showing significant Holocene environmental variability: The inner N. Iceland shelf (Húnaflói). *Quaternary Science Reviews* 22: 175–193.

Ascough PL, Cook GT, Church MJ et al. (2007) Reservoirs and radiocarbon: 14C dating problems in Myvatnssveit, Northern Iceland. *Radiocarbon* 49: 947 961.

Atkinson M (1992) Betula pendula Roth (*B. verrucosa* Ehrh.) and *B. pubescens* Ehrh. *Journal of Ecology* 80: 837–870.

Axford Y, Miller GH, Geirsdóttir Á et al. (2007) Holocene temperature history of northern Iceland inferred from subfossil midges. *Quaternary Science Reviews* 26: 3344 3358.

Bengtsson L and Enell M (1986) Chemical analysis. In: Berglund BE (ed.) *Handbook of Holocene Palaeoecology and Palaeohydrology*. Chichester: John Wiley & Sons, pp. 423–451.

Bennett KD (2007) Catalogue of pollen types. Available at: http://www.chrono.qub.ac.uk/pollen/pc-intro.html (accessed 26 November 2014).

Berger A and Loutre M-F (1991) Insolation values for the climate of the last 10 million years. *Quaternary Science Reviews* 10: 297 317. Available at: https://www.ncdc.noaa.gov/paleo/study/5776 (accessed 17 May 2015).

Berggren G (1969) *Atlas of Seeds and Small Fruits of Northwestern-European Plant Species (Sweden, Norway, Denmark, East Fennoscandia and Iceland) with Morphological Descriptions. Part 2: Cyperaceae*. Stockholm: Swedish Natural Science Research Council.

Bergþórsson P (1969) Hafísinn og hitastig á liðnum öldum. In: Einarsson MÁ (ed.) *Hafísinn*. Reykjavík: Almenna Bókafélagið, pp. 333 345.

Birks HH (2007) Plant macrofossils Introduction. In: Elias SA (ed.) *Encyclopedia of Quaternary Science*. 2nd Edition. Amsterdam: Elsevier, pp. 2266–2288.

Birks HH and Birks HJB (2000) Future uses of pollen analysis must include plant macrofossils. *Journal of Biogeography* 27: 31 35.

Birks HH and Birks HJB (2014) To what extent did changes in July temperature influence Lateglacial vegetation patterns in NW Europe? *Quaternary Science Reviews* 106: 262–277.

Birks HH and Bjune AE (2010) Can we detect a west Norwegian tree line from modern samples of plant remains and pollen? Results from the DOORMAT project. *Vegetation History and Archaeobotany* 19: 325–340.

Birks HJB (1973) Modern pollen studies in some arctic and alpine environments. In: Birks HJB and West RG (eds) *Quaternary Plant Ecology*. Oxford: Blackwell, pp. 143 168.

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

Björck S, Ingólfsson Ó, Hafliðason H et al. (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: 15–22.

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

Brady NC and Weil RR (1996) *The Nature and Properties of Soils*. Upper Saddle River, NJ: Prentice Hall.

Bronk Ramsey C and Lee S (2013) Recent and planned developments of the program OxCal. *Radiocarbon* 55: 720–730.

Cappers RTJ, Bekker RM and Jans JEA (2012) *Digitale Zadenatlas van Nederland*. Groningen: Barkhuis Publishing and Groningen University Library.

Caseldine C and Hatton J (1994) Interpretation of Holocene climatic change for the Eyjafördur area of northern Iceland from pollen-analytical data: Comments and preliminary results. *Environmental Change in Iceland: Münchener Geographische Abhandlungen, Reihe B* 12: 41 42.

Caseldine C, Geirsdóttir Á and Langdon P (2003) Efstadalsvatn – A multi-proxy study of a Holocene lacustrine sequence from NW Iceland. *Journal of Paleolimnology* 30: 55–73.

Caseldine C, Langdon P and 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: 2314–2331.

Castañeda IS, Smith LM, Kristjánsdóttir GB et al. (2004) Temporal changes in Holocene δ18O records from the northwest and central North Iceland Shelf. *Journal of Quaternary Science* 19: 321–334.

Cugny C, Mazier F and 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: 391–408.

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

Dieffenbacher-Krall AC (2007) Surface samples, taphonomy, representation. In: Elias SA (ed.) *Encyclopedia of Quaternary Science*. Amsterdam: Elsevier, pp. 2367–2374.

Dugmore AJ, Cook GT, Shore JS et al. (1995) Radiocarbon dating tephra layers in Britain and Iceland. *Radiocarbon* 37: 379 388.

Eiriksson J, Knudsen KL, Haflidason H et al. (2000) Late-glacial and Holocene palaeoceanography of the North Icelandic shelf. *Journal of Quaternary Science* 15: 23–42.

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

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

Erlendsson E, Vickers K, Bending JM et al. (2012) Late-Holocene environmental history of the Reykholt area, Borgarfjörður, Western Iceland. In: Þorláksson H and Sigurðardóttir ÞB (eds) *From Nature to Script*. Reykholt: Snorrastofa, pp. 17 47.

Eynaud F, Turon JL and Duprat J (2004) Comparison of the Holocene and Eemian palaeoenvironments in the South Icelandic Basin: Dinoflagellate cysts as proxies for the North Atlantic surface circulation. *Review of Palaeobotany and Palynology* 128: 55 79.

Faegri K and Iversen J (1989) *Textbook of Pollen Analysis* (revised by K Faegri, PE Kaland and K Krzywinski). New York: John Wiley & Sons.

García D, Zamora R, Gómez JM et al. (2000) Geographical variation in seed production, predation and abortion in *Juniperus communis* throughout its range in Europe. *Journal of Ecology* 88: 435–446.

Gathorne-Hardy FJ, Erlendsson E, Langdon PG et al. (2009) Lake sediment evidence for late Holocene climate change and landscape erosion in western Iceland. *Journal of Paleolimnology* 42: 413–426.

Geirsdóttir Á, Miller GH, Axford Y et al. (2009) Holocene and latest Pleistocene climate and glacier fluctuations in Iceland. *Quaternary Science Reviews* 28: 2107 2118.

Geirsdóttir Á, Miller GH, Larsen DJ et al. (2013) Abrupt Holocene climate transitions in the northern North Atlantic region recorded by synchronized lacustrine records in Iceland. *Quaternary Science Reviews* 70: 48–62.

Gimingham C (1984) Ecological aspects of birch. *Proceedings of the Royal Society of Edinburgh, Section B: Biological Sciences* 85: 65–72.

Giraudeau J, Jennings AE and Andrews JT (2004) Timing and mechanisms of surface and intermediate water circulation changes in the Nordic Seas over the last 10,000 cal years: A view from the North Iceland shelf. *Quaternary Science Reviews* 23: 2127–2139.

Gisladottir FO, Arnalds O and Gisladottir G (2005) The effect of landscape and retreating glaciers on wind erosion in South Iceland. *Land Degradation & Development* 16: 177–187.

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

Gísladóttir G, Erlendsson E, Lal R et al. (2010) Erosional effects on terrestrial resources over the last millennium in Reykjanes, southwest Iceland. *Quaternary Research* 73: 20–32.

Grimm EC (2011) *TILIA* (version 1.7. 16). Springfield, IL: Illinois State Museum.

Gudmundsdóttir ER, Larsen G and Eiríksson J (2011) Two new Icelandic tephra markers: The Hekla Ö tephra layer, 6060 cal. yr BP, and Hekla DH tephra layer, ~6650 cal. yr BP. Land-sea correlation of mid-Holocene tephra markers. *The Holocene* 21: 629–639.

Gudmundsdóttir ER, Larsen G and Eiríksson J (2012) Tephra stratigraphy on the North Icelandic shelf: Extending tephrochronology into marine sediments off North Iceland. *Boreas* 41: 718–734.

Guðbergsson G (1996) Í norðlenskri vist. Um gróður, jarðveg, búskaparlög og sögu. *Búvísindi* 10: 31–89.

Hallgrímsson H and Eyjólfsdóttir GG (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 Thesis, Lund University.

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

Hallsdóttir M and Caseldine CJ (2005) The Holocene vegetation history of Iceland, state-of-the-art and future research. In: Caseldine C, Russel A, Harðardóttir J et al. (eds) *Iceland – Modern Processes and Past Environments*. Amsterdam: Elsevier, pp. 319–334.

Hicks S (2001) The use of annual arboreal pollen deposition values for delimiting tree-lines in the landscape and exploring models of pollen dispersal. *Review of Palaeobotany and Palynology* 117: 1–29.

Huntley B and Birks HJB (1983) *An Atlas of Past and Present Pollen Maps for Europe: 0–13000 Years Ago*. Cambridge: Cambridge University Press.

Icelandic Met Office (2014) Mánaðarmeðaltöl/Monthly data. Available at: http://www.vedur.is/Medaltalstoflur-txt/Manadargildi.html (accessed 11 November 2014).

Jackson ST and Booth RK (2007) Validation of pollen studies. In: Elias SA (ed.) *Encyclopedia of Quaternary Science*. Amsterdam: Elsevier, pp. 2413–2422.

Jennings A, Andrews J and Wilson L (2011) Holocene environmental evolution of the SE Greenland Shelf North and South of the Denmark Strait: Irminger and East Greenland current interactions. *Quaternary Science Reviews* 30: 980–998.

Jennings A, Thordarson T, Zalzal K et al. (2014) Holocene tephra from Iceland and Alaska in SE Greenland Shelf Sediments. In: Austin WEN, Abbott PM, Davies SM et al. (eds) *Marine Tephrochronology*. London: Geological Society (Special Publications 398). Available at: http://sp.lyellcollection.org/content/early/2014/02/25/SP398.6.

Jónsson ÞH (2005) Útbreiðsla birkis á Íslandi. *Skógræktarritið* 2: 61–71.

Justwan A, Koç N and Jennings AE (2008) Evolution of the Irminger and East Icelandic Current systems through the Holocene, revealed by diatom-based sea surface temperature reconstructions. *Quaternary Science Reviews* 27: 1571–1582.

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

Karlsdóttir L, Hallsdóttir M, Thórsson ÆT et al. (2008) Characteristics of pollen from natural triploid Betula hybrids. *Grana* 47: 52–59.

Karlsdóttir L, Hallsdóttir M, Thórsson ÆT et al. (2009) Evidence of hybridisation between *Betula pubescens* and *B. nana* in Iceland during the early Holocene. *Review of Palaeobotany and Palynology* 156: 350–357.

Karlsdóttir L, Hallsdóttir M, Thórsson ÆT et al. (2012) Early Holocene hybridisation between *Betula pubescens* and *B. nana* in relation to birch vegetation in Southwest Iceland. *Review of Palaeobotany and Palynology* 181: 1–10.

Katz NJ, Katz SV and Kipiani MG (1965) *Atlas and Keys of Fruits and Seeds Occurring in the Quaternary Deposits of the USSR*. Moscow: Publishing House Nauka.

Kauppi A, Rinne P and Ferm A (1987) Initiation, structure and sprouting of dormant basal buds in *Betula pubescens*. *Flora* 179: 55–83.

Knudsen K, Jiang H, Jansen E et al. (2004) Environmental changes off North Iceland during the deglaciation and the Holocene: Foraminifera, diatoms and stable isotopes. *Marine Micropaleontology* 50: 273–305.

Knudsen KL, Søndergaard MKB, Eiríksson J et al. (2008) Holocene thermal maximum off North Iceland: Evidence from benthic and planktonic foraminifera in the 8600–5200 cal year BP time slice. *Marine Micropaleontology* 67: 120–142.

Kolstrup E (1979) Herbs as July temperature indicators for parts of the pleniglacial and late-glacial in the Netherlands. *Geologie en Mijnbouw* 58: 377–380.

Kolstrup E (1980) *Climate and Stratigraphy in Northwestern Europe between 30,000 BP and 13,000 BP with Special Reference to the Netherlands* (*Volume 31 of Publicaties van het Fysisch Geografisch en Bodemkundig Laboratorium van de Universiteit van Amsterdam*). Haarlem: Rijks Geologische Dienst.

Kristinsson H (2010) *Flowering Plants and Ferns of Iceland*. Reykjavík: Mál og Menning.

Langdon PG, Leng M, Holmes N et al. (2010) Lacustrine evidence of early-Holocene environmental change in northern Iceland: A multiproxy palaeoecology and stable isotope study. *The Holocene* 20: 205–214.

Larsen DJ, Miller GH, Geirsdóttir Á et al. (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 Thorarinsson S (1977) H4 and other acid Hekla tephra layers. *Jökull* 27: 28–46.

Lawson IT, Gathorne-Hardy FJ, Church MJ et al. (2007) Environmental impacts of the Norse settlement: Palaeoenvironmental data from Myvatnssveit, northern Iceland. *Boreas* 36: 1–19.

Marteinsdóttir B, Svavarsdóttir K and Þórhallsdóttir ÞE (2007) Landnám birkis á Skeiðarársandi. *Náttúrufræðingurinn* 75: 123–129.

Moore PD, Webb JA and Collison ME (1991) *Pollen Analysis*. Oxford: Blackwell Scientific Publications.

Mortensen MF, Henriksen PS and Bennike O (2014) Living on the good soil: Relationships between soils, vegetation and human settlement during the late Allerød period in Denmark. *Vegetation History and Archaeobotany* 23: 195–205.

Nakagawa T, Brugiapaglia E, Digerfeldt G et al. (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.

Ogilvie AEJ (1984) The past climate and sea-ice record from Iceland. Part 1: Data to AD 1780. *Climatic Change* 6: 131–152.

Ogilvie AEJ (1992) Documentary evidence for changes in the climate of Iceland AD 1500 to 1800. In: Bradley RS and Jones PD (eds) *Climate since AD 1500*. London and New York: Routledge, pp. 92–117.

Ogilvie AEJ and Jónsdóttir I (2000) Sea ice, climate, and Icelandic fisheries in the eighteenth and nineteenth centuries. *Arctic* 53: 383–394.

Ogilvie AEJ and Jónsson T (2001) 'Little Ice Age' research: A perspective from Iceland. *Climatic Change* 48: 9–52.

Persson Å (1964) The vegetation at the margin of the receding glacier Skaftafellsjökull, Southeastern Iceland. *Botaniska Notiser* 117: 323–354.

Pichugina NP (1972) Effect of ecological factors on seed formation in certain interspecific birch hybrids. *Ecologiya: The Soviet Journal of Ecology* 6: 89–91.

Ran L, Jiang H, Knudsen KL et al. (2006) Diatom response to the Holocene climatic optimum on the North Icelandic shelf. *Marine Micropaleontology* 60: 226–241.

Ran L, Jiang H, Knudsen KL et al. (2008) A high-resolution Holocene diatom record on the North Icelandic shelf. *Boreas* 37: 399–413.

Rasmussen SO, Andersen KK, Svensson AM et al. (2006) A new Greenland ice core chronology for the last glacial termination. *Journal of Geophysical Research: Atmospheres* 111: D06102.

Reimer PJ, Bard E, Bayliss A et al. (2013) IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. *Radiocarbon* 55: 1869–1887.

Rousse S, Kissel C, Laj C et al. (2006) Holocene centennial to millennial-scale climatic variability: Evidence from high-resolution magnetic analyses of the last 10 cal kyr off North Iceland (core MD99–2275). *Earth and Planetary Science Letters* 242: 390–405.

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

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

Rundgren M and Ingólfsson Ó (1999) Plant survival in Iceland during periods of glaciation? *Journal of Biogeography* 26: 387–396.

Schofield JE, Edwards KJ and 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: 473–488.

Seppä H and Hicks S (2006) Integration of modern and past pollen accumulation rate (PAR) records across the arctic tree-line: A method for more precise vegetation reconstructions. *Quaternary Science Reviews* 25: 1501–1516.

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

Stötter J, Wastl M, Caseldine C et al. (1999) Holocene palaeoclimatic reconstruction in northern Iceland: Approaches and results. *Quaternary Science Reviews* 18: 457–474.

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

Thomas ER, Wolff EW, Mulvaney R et al. (2007b) The 8.2 ka event from Greenland ice cores. *Quaternary Science Reviews* 26: 70–81.

Thomas PA, El-Barghathi M and Polwart A (2007a) Biological flora of the British Isles: *Juniperus communis L. Journal of Ecology* 95: 1404–1440.

Thorarinsson S (1971) The age of the light Hekla tephra layers according to corrected C14-datings. *Náttúrufræðingurinn* 41: 99–105.

Thórsson ÆT, Salmela E and Anamthawat-Jónsson K (2001) Morphological, cytogenetic, and molecular evidence for introgressive hybridization in birch. *Journal of Heredity* 92: 404–408.

Van Geel B, Buurman J, Brinkkemper O et al. (2003) Environmental reconstruction of a Roman Period settlement site in Uitgeest (The Netherlands), with special reference to coprophilous fungi. *Journal of Archaeological Science* 30: 873–883.

Vasari Y (1972) The history of the vegetation in Iceland during the Holocene. In: Vasari Y, Hyvärinen H and Hicks S (eds) *Climatic Changes in Arctic Areas during the Last Ten-Thousand Years*. Oulu: University of Oulu, pp. 239–252.

Vasari Y (1973) Post-glacial plant succession in Iceland before the period of human interference. In: Khotinsky NA (ed.) *Palynology of Holocene: Proceedings of the 3rd International Palynological Conference*. Moscow: Publishing House Nauka, pp. 7–14.

Vasari Y and Vasari A (1990) L'histoire Holocéne des lacs Islandais. In: Malaurie J (ed.) *102 témoignages en hommage á quarante ans d'études arctiques*. Paris: Éditions Plon, pp. 279–293.

Verwijst T (1988) Environmental correlates of multiple-stem formation in *Betula pubescens* ssp. *tortuosa*. *Vegetatio* 76: 29–36.

Vickers K, Erlendsson E, Church MJ et al. (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: 979–995.

Vilmundardóttir OK, Gísladóttir G and Lal R (2014) Early stage development of selected soil properties along the proglacial moraines of Skaftafellsjökull glacier, SE-Iceland. *Catena* 121: 142–150.

Vilmundardóttir OK, Gísladóttir G and Lal R (2015) Soil carbon accretion along an age chronosequence formed by the retreat of the Skaftafellsjökull glacier, SE-Iceland. *Geomorphology* 228: 124–133.

Vilmundardóttir OK, Magnússon B, Gísladóttir G et al. (2009) Gróðurframvinda í áfoksgeira i mólendi við Blöndulón. *Náttúrufræðingurinn* 78: 125–137.

Vinther BM, Buchardt SL, Clausen HB et al. (2009) Holocene thinning of the Greenland ice sheet. *Nature* 461: 385–388. Available at: https://www.ncdc.noaa.gov/paleo/study/11148 (accessed 17 May 2015).

Wastl M, Stötter J and 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: 191–203.

Wöll C (2008) *Treeline of mountain birch (Betula pubescens Ehrh.) in Iceland and its relationship to temperature*. MSc Thesis, Technische Universität Dresden.

Appendix 1. Results from scanning electron microscope analyses of major elemental composition of key tephra layers in the KAGA (Kagaðarhóll) and BUR (Stóra-Búrfell) sequences.

Site	Depth (cm)	Av./SD	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	SUM	Tephra	#
KAGA	139–140	Av.	66.91	0.39	15.50	6.63	0.21	0.41	3.85	3.61	2.38	0.12	100.00	Hekla 3	8
		SD	2.06	0.16	0.35	1.24	0.08	0.20	0.53	0.17	0.33	0.07			
KAGA	202–203	Av.	74.83	0.15	13.83	2.35	0.12	0.15	1.62	3.38	3.51	0.05	100.00	Hekla 4	7
		SD	0.20	0.06	0.17	0.12	0.06	0.03	0.08	0.19	0.13	0.03			
KAGA	221–222	Av.	64.00	0.87	16.50	6.39	0.18	0.73	3.30	3.97	3.91	0.16	100.00	Ssn	11
		SD	2.11	0.30	0.20	1.11	0.07	0.41	0.77	0.25	0.66	0.07			
KAGA	266–267	Av.	56.48	2.24	15.98	10.08	0.19	2.55	6.52	3.55	2.13	0.27	100.00	Hekla	7
		SD	0.28	0.19	0.73	0.55	0.04	0.24	0.26	0.15	0.35	0.04			
KAGA	290–291	Av.	60.52	1.05	16.69	9.02	0.21	0.97	6.00	3.57	1.65	0.31	100.00	Hekla Ö	9
		SD	0.50	0.26	1.43	1.66	0.04	0.27	0.70	0.20	0.19	0.06			
KAGA	319–320	Av.	48.43	4.56	12.80	15.67	0.23	4.83	10.08	2.30	0.83	0.26	100.00	Katla S	8
		SD	0.44	0.10	0.25	0.63	0.10	0.13	0.34	0.08	0.06	0.05			
KAGA	360–361	Av.	75.57	0.12	13.33	2.24	0.13	0.15	1.65	3.25	3.53	0.04	100.00	Hekla 5	8
		SD	0.23	0.08	0.15	0.18	0.06	0.04	0.12	0.10	0.13	0.00			
KAGA	633–634	Av.	49.78	3.28	12.93	15.42	0.20	5.30	10.37	2.15	0.42	0.14	100.00	Saksunarvatn	10
		SD	0.32	0.26	0.32	0.44	0.09	0.40	0.33	0.09	0.04	0.03			
BUR	80–80.5	Av.	57.18	1.93	14.66	11.62	0.28	2.36	6.56	3.29	1.58	0.53	100.00	Hekla[a]	6
		SD	0.11	0.15	0.31	0.26	0.04	0.16	0.08	0.14	0.17	0.04			
BUR	89–90	Av.	63.69	0.89	16.43	6.50	0.20	0.71	3.28	4.07	4.08	0.15	100.00	Ssn	10
		SD	1.72	0.35	0.22	0.91	0.09	0.34	0.80	0.17	0.73	0.09			
BUR	98.5–99	Av.	57.07	2.24	16.08	9.71	0.18	2.41	6.36	3.57	2.09	0.29	100.00	Hekla	7
		SD	0.68	0.31	0.87	0.84	0.10	0.49	0.16	0.16	0.11	0.06			
BUR	113–114	Av.	60.93	1.12	15.46	10.04	0.23	1.08	5.42	3.52	1.85	0.34	100.00	Hekla Ö	9
		SD	0.74	0.20	1.39	1.43	0.06	0.27	0.31	0.20	0.29	0.04			
BUR	134–135	Av.	48.82	4.46	13.08	15.03	0.19	4.91	9.86	2.54	0.81	0.31	100.00	Katla S	8
		SD	0.46	0.16	0.23	0.37	0.03	0.12	0.34	0.10	0.11	0.04			

[a]Analysis of the upper, basaltic part of the Hekla 4 tephra (cf. Larsen and Thorarinsson, 1977).

Supplementary material

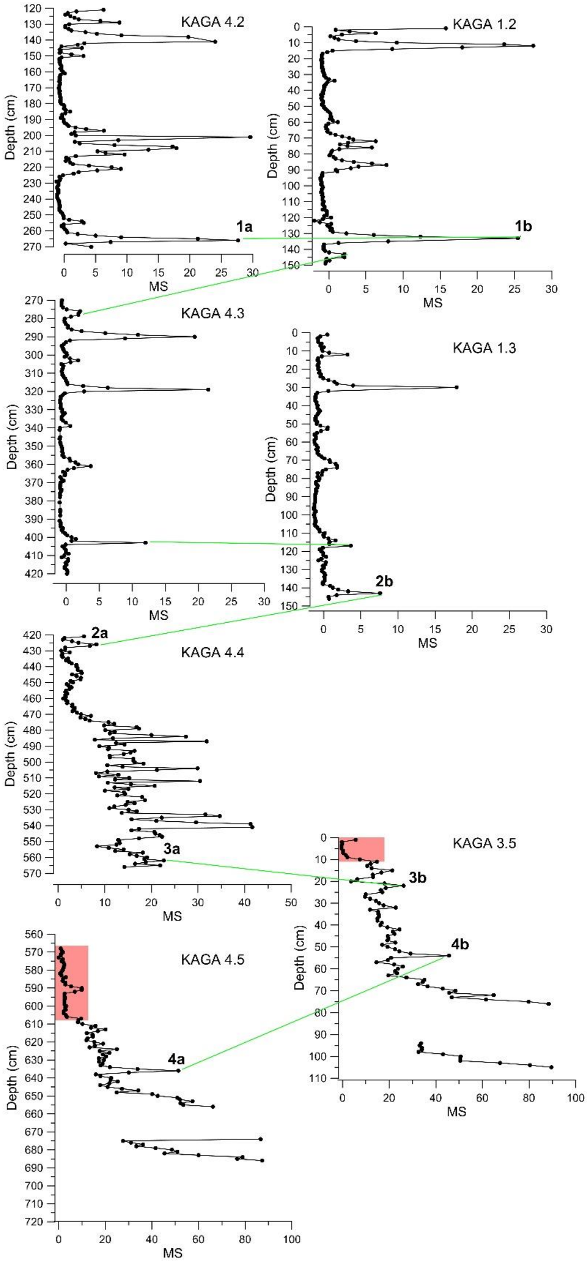

Figure 1. Magnetic susceptibility (MS) measurements (showing arbitrary values below 100) from the main cores sequence KAGA 4 and overlapping core segments from KAGA 1 and KAGA 3. Green lines connect corresponding points in different core segments. Red segments represent sediments disturbed during coring. Numbers denote analysed tephra layers (see Figure 2).

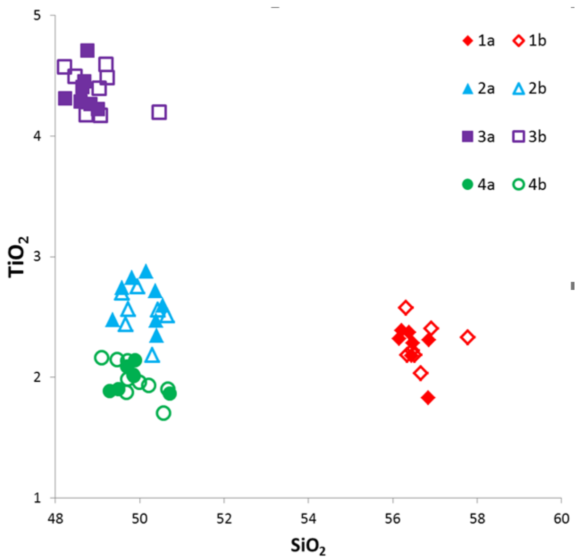

Figure 2. Plot showing SEM-derived SiO_2 and TiO_2 content (wt %) of shards from tephra layers connecting the overlapping core segments and the KAGA 4 sequence (see placements in Figure 1; methods are detailed in the paper's methods section). Origins of tephras are colour coated according to recent literature (e.g. Óladóttir et al., 2011; Gudmundsdóttir et al., 2012): red: Hekla, violet: Katla, blue: Grímsvötn, green: Bárðarbunga.

Paper II

Climate change and human impact in a sensitive ecosystem: the Holocene environment of the Northwest Icelandic highland margin

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Climate change and human impact in a sensitive ecosystem: the Holocene environment of the Northwest Icelandic highland margin

SIGRÚN D. EDDUDÓTTIR, EGILL ERLENDSSON, LEONE TINGANELLI AND GUÐRÚN GÍSLADÓTTIR

BOREAS

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Complex interactions of climate and volcanic activity have shaped the environment of Iceland during the Holocene. Palaeoecological records from Iceland offer a unique look at a Holocene environment that was uninhabited by humans and free of mammal herbivores until about AD 870. We present a new reconstruction of Holocene vegetation and landscape dynamics from a small lake, Barðalækjartjörn, located near the highland margin in Northwest Iceland. A multi-proxy approach was used to reconstruct vegetation based on pollen and plant macrofossil analysis and landscape stability based on lithological proxies. The record covers the period *c.* 10 300–200 cal. a BP. For the first two millennia aeolian processes probably played a part in vegetation development. This period is characterized by high input of minerogenic material into the lake and a vegetation assemblage in which plants tolerant of aeolian deposition are prominent. *Betula pubescens* woodland reached a maximum between *c.* 7400 and 6500 cal. a BP. *Betula nana*-dominated dwarf shrub heath replaced woodland after *c.* 4000 cal. a BP, following the onset of Neoglaciation. Land use following human settlement caused an environmental shift at the highland margin. *Betula pubescens* probably disappeared from the vicinity of the lake soon thereafter. Large-scale soil erosion began at *c.* 1000 cal. a BP in the wake of human activities, such as introduction of grazing livestock and woodcutting. This study offers an important long-term perspective of the development of the highland ecosystem under both wholly natural and human-influenced conditions.

Sigrún D Eddudóttir (sde6@hi.is), Egill Erlendsson and Leone Tinganelli, Institute of Life and Environmental Sciences, University of Iceland, Sturlugata 7, 101 Reykjavík, Iceland; Guðrún Gísladóttir, Institute of Life and Environmental Sciences and Institute of Earth Sciences, University of Iceland, Sturlugata 7, 101 Reykjavík, Iceland;
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Iceland's position as a terrestrial outpost in the North Atlantic makes it an important site for studies of Holocene environmental conditions in the region. Prior to the Norse settlement (*c.* AD 870) Iceland was free of human influence and without native mammal herbivores. Iceland therefore offers an opportunity to study an isolated Holocene environment where changes were dictated mainly by climate. Intermittent volcanic events also caused disturbances and increased landscape instability, usually on short time scales (Gísladóttir *et al.* 2010; Larsen *et al.* 2012; Blair *et al.* 2015; Eddudóttir *et al.* 2015). Following settlement, the landscape and vegetation were radically altered by human activities (Einarsson 1961; Hallsdóttir 1987; Erlendsson 2007). The settlement probably happened rapidly and an estimated minimum of 24 000 people were living in Iceland by the end of the 9th century AD, with a continued influx of people throughout the 10th century (Vésteinsson & McGovern 2012). The settlers soon began clearing woodland to make way for grazing pastures as well as utilizing it for fuel and building material (Hallsdóttir 1987; Dugmore *et al.* 2005; Vickers *et al.* 2011). This external disturbance caused habitat changes that led to accelerated soil erosion as resilient woodland habitats were replaced by grassland and dwarf shrub heath (Dugmore *et al.* 2005, 2009; McGovern *et al.* 2007; Gathorne-Hardy *et al.* 2009; Gísladóttir *et al.* 2011; Vickers *et al.* 2011). The cumulative effects of human settlement, cooling climate within the last few millennia and frequent volcanic eruptions (Thordarson & Larsen 2007; Larsen & Eiriksson 2008) have moulded a modern environment that is vastly different from that of the mid-Holocene (Hallsdóttir 1995; Hallsdóttir & Caseldine 2005; Caseldine *et al.* 2006; Eddudóttir *et al.* 2015).

Iceland's interior above 400 m a.s.l. is classified as highland and covers about 40% of the island. The highland has a sub-arctic climate in contrast with the cold temperate climate in lowland areas. The highland margin therefore represents an important boundary between climate regimes resulting in an ecotone between low arctic tundra and sub-arctic birch forest (Jónsdóttir *et al.* 2005). At present, a large part of the highland is classified as desert, despite a relatively humid climate. A complex interplay of processes has been involved in the creation of these deserts, mainly land use, volcanism, climate and, locally, flooding (Arnalds 2015).

Downy birch (*Betula pubescens* Ehrh.) and its subspecies mountain birch (*Betula pubescens* ssp. *tortuosa*) are the only woodland-forming tree species in Iceland. Modern individuals of *Betula pubescens* Ehrh. and subspecies *tortuosa* are morphologically indistinguishable in Iceland (Thórsson *et al.* 2001, 2007) and together they are therefore referred to as *Betula pubescens* sensu lato. Growth and distribution of *Betula pubescens* in Iceland is strongly correlated with tritherm temperatures (mean of the three warmest summer months, June, July and August). At present, tree lines in Iceland are located between 260 and 500 m a.s.l. (Jónsson 2005). Inland, the

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tree line (trees over 2 m) correlates with a tritherm temperature of 7.9 °C and the species distribution limit with 7.2 °C (Wöll 2008). Therefore, in pre-settlement Iceland, birch woodland would have extended to higher elevations during periods of higher summer temperatures and regressed to lower altitudes during periods of cold summers. Records of Holocene vegetation in highland environments should therefore be sensitive to changes in tree-line location due to climate change.

The extent and altitude of pre-settlement woodlands in Iceland are debated. The scarcity of available vegetation reconstructions from highland environments makes estimates of woodland extent during the pre-settlement Holocene difficult. Many palaeoenvironmental reconstructions have been made for Iceland (Hallsdóttir 1995; Rundgren 1998; Wastl *et al.* 2001; Caseldine *et al.* 2003, 2006; Hallsdóttir & Caseldine 2005; Erlendsson 2007; Geirsdóttir *et al.* 2009, 2013; Langdon *et al.* 2010; Larsen *et al.* 2012; Striberger *et al.* 2012; Blair *et al.* 2015; Eddudóttir *et al.* 2015). However, only two vegetation reconstructions exist for sites above 400 m a.s.l. (Hallsdóttir 1982; Wastl *et al.* 2001).

In this paper we present a new reconstruction of Holocene vegetation and landscape dynamics, for Barðalækjartjörn, a small lake located at the highland margin in Northwest Iceland. This paper examines terrestrial ecosystem development in a highland setting from the early Holocene to *c.* 200 cal. a BP and investigates potential drivers for ecosystem change over the period. We specifically aimed to examine: (i) early Holocene vegetation communities during the first stages of postglacial succession; (ii) the possible timing, extent and duration of birch woodland colonization on the highland margin; and (iii) the relative importance of post-settlement land use in shaping the present-day eroded landscape of the highland. To achieve this task a multi-proxy approach was employed, i.e. a vegetation reconstruction based on both pollen and plant macrofossils, as well as a reconstruction of landscape stability through several lithological proxies. The study offers an important long-term perspective concerning the development of the highland ecosystem under both natural and human-influenced conditions.

Site description

Barðalækjartjörn lake (BART; altitude 413 m a.s.l.; latitude 65°25 212′N, longitude 19°52 388′W) is located on Auðkúluheiði heath on the northern margin of the central highland (Fig. 1). The lake is about

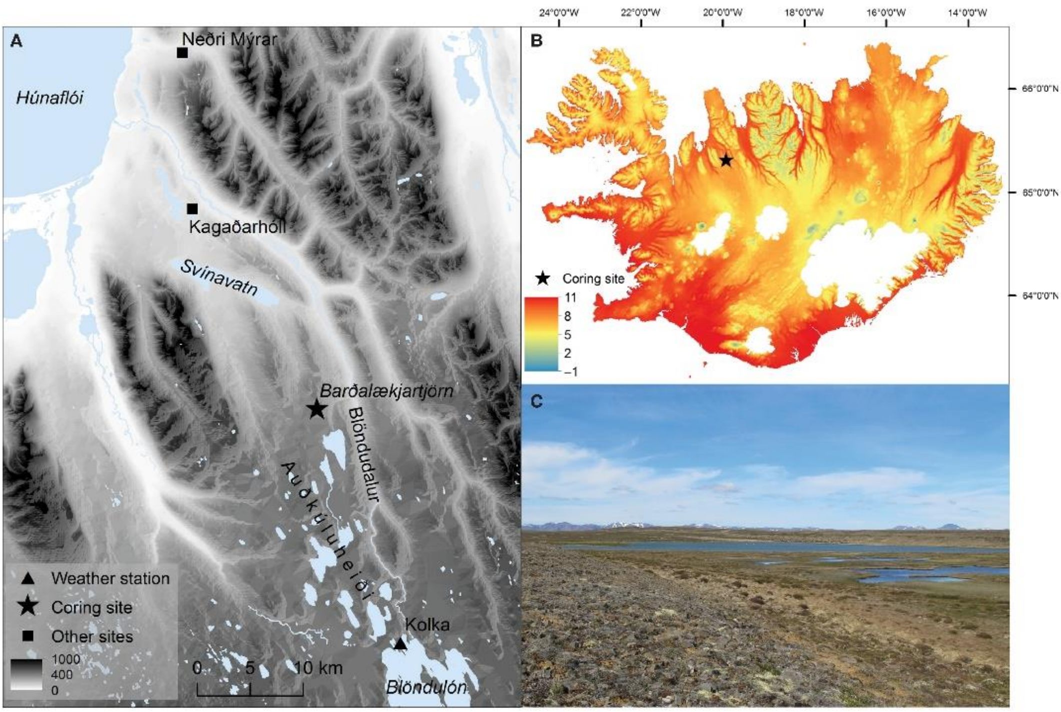

Fig. 1. The Barðalækjartjörn study site. A. Map showing the location of Barðalækjartjörn and other sites in the region mentioned in the text. B. Map of Iceland showing the mean tritherm (mean June, July and August) temperature and the location of the coring site. C. Photograph of Barðalækjartjörn and its surroundings. [Colour figure can be viewed at wileyonlinelibrary.com]

10 ha in area and is located ~ 20 km north of Blöndulón hydro-electric reservoir. The closest inhabited settlements are farms located ~4 km away in Blöndudalur valley (Fig. 1). The lake is surrounded by *Carex*-dominated wetlands, *Betula nana*, *Calluna vulgaris* and *Salix* spp. dwarf shrub heath, large vegetated hummocks and eroded, gravelly hills (Fig. 1). There is no surface inflow into the lake but a small outlet drains the lake from the northwest corner of the lake through nearby wetland. The lake is located on private land close to the boundary of communal grazing areas of Auðkúluheiði. The area was used as communal grazing land (Magnússon & Vídalín 1926) prior to being fenced off in recent decades. The vegetation and soils in the area have been extensively influenced by land use since the settlement (Guðbergsson 1996). Weather observations from Kolka weather station, located at the northern end of the nearby Blöndulón reservoir (504 m a.s.l.), are available for 1994–2014. The mean tritherm (mean June, July and August) summer temperature for the period was ~7.8 °C and the mean July temperature was ~8.8 °C. The annual precipitation was ~398 mm per year (Icelandic Met Office 2014). The mean minimum tritherm temperature is above the temperature limit for birch tree growth in Iceland (7.2 °C; Jónsson 2005; Wöll 2008). It should be noted that the weather station is located about 91 m a.s.l. higher than Barðalækjartjörn and so the temperature is probably slightly warmer at the lake. Calculated from the average adiabatic lapse rate (0.65 °C), the altitudinal difference between the two locations translates to a ~0.59 °C difference in temperature. Rainfall and wind speed are probably similar in both locations as the area is relatively flat.

Methods

Field methods, stratigraphy and geochemistry

Four series of overlapping sediment cores were retrieved from the centre of the lake at ~90 cm water depth. Three series (BART 1, 3 and 4) were cored using a Livingstone piston corer with a Bolivia adaptor fitted with 75-mm diameter polycarbonate tubes. One series was retrieved using a 100-cm-long Russian corer with a chamber diameter of 10 cm (BART 5). The sediments consisted of silty gyttja with intermittent tephra layers and a 35-cm-thick mixed sand and tephra layer at the bottom. By correlating tephra layers, changes in stratigraphy and changes in magnetic susceptibility, a single depth profile was constructed by overlapping the main succession of cores (BART 1) with cores from two other sequences (BART 3 and 5), to ensure continuity in the sediment column (Fig. S1). Microprobe analysis of tephra layers were used as correlation points (Fig. S2). The resulting sediment succession was 295 cm long; the lowermost 35 cm of sand and tephra were not included in the palaeoecological reconstruction. Although the lake is relatively shallow there are no indications of hiatuses in the sediment and no signs of the lake drying out during the Holocene. However, the possibility of wave action affecting the top of the sediment column cannot be excluded, especially in the uppermost part of the core.

The cores were X-rayed. Magnetic susceptibility (MS) was measured with a Bartington MS2 meter and Bartington MS2F probe at 1-cm intervals on split core segments (Dearing 1994). Dry bulk density (DBD; g cm^{-3}) and organic matter (OM, measured by loss on ignition) were measured at 1-cm contiguous intervals. OM was measured by combusting 1.2 cm^3 of sample at 550 °C for 5 h (Bengtsson & Enell 1986). DBD was calculated by dividing the dry weight of a sample by the volume of the undisturbed sample (Brady & Weil 1996). Subsamples analysed for carbon and nitrogen were taken at contiguous 2-cm intervals. The samples were dried at 50 °C, ground and sieved through a 150 μm mesh before weighing in a tin container. The measurements were taken by dry combustion on a Flash 2000 Elemental Analyzer (Thermo-Scientific, Italy). The sediments analysed for this study cover the period from *c.* 10 300 to 200 cal. a BP.

Pollen and plant macrofossil analysis

Samples for pollen analysis were collected at 1 to 8 cm intervals. Pollen samples were prepared from 2 cm^3 of sediment using standard chemical methods with 10% HCl, 10% NaOH, acetolysis (Fægri *et al.* 1989; Moore *et al.* 1991) and heavy-liquid separation using LST Fastfloat (a sodium heteropolytungstate solution; density 1.9 g cm^{-3}; Björck *et al.* 1978; Nakagawa *et al.* 1998). Two tablets containing spores of *Lycopodium clavatum* (batch no. 177745) were added to each sample (Stockmarr 1971) to enable calculations of pollen accumulation rates (PAR; grains cm^{-2} a^{-1}). For each sample a minimum of 300 indigenous terrestrial pollen grains was counted. Identification of pollen grains and spores relied on Moore *et al.* (1991) and a pollen type slide collection at the University of Iceland. Pollen and spore taxonomy followed Bennett (2007) and Erlendsson (2007) and pollen categories and calculations followed Hallsdóttir (1987) and Caseldine *et al.* (2006). Coprophilous fungal spores were identified according to van Geel *et al.* (2003) and their percentages were calculated based on the combined sum of terrestrial pollen and coprophilous fungal spores. Measurements were taken of *Betula* pollen diameters at 1000× magnification. Non-triporate *Betula* pollen grains were recorded as they may be an indicator of hybridization between *Betula nana* and *Betula pubescens* (Karlsdóttir *et al.* 2008).

Plant macrofossil samples were analysed at contiguous 5-cm intervals. The volume of each sample was measured by displacement in water; sample volume varied between 40 and 51 mL. Samples were washed through a 125-μm sieve and vascular plant remains were picked out for identification. Identification was based on various references (e.g. Katz *et al.* 1965; Berggren 1969; Birks 2007; Cappers *et al.* 2012) and comparisons with reference material when available. Plant taxonomy follows Kristinsson (2010). Concentrations of plant macrofossils in 50 mL of sediment were calculated. Pollen and macrofossil diagrams were constructed using TILIA (version 1.7.16; Grimm 2011) and pollen zones (PZs) were calculated in TILIA using CONISS based on terrestrial pollen assemblages.

Principal component analysis

To detect patterns in terrestrial vegetation development in the vicinity of Barðalækjartjörn, ordination methods were performed in R using the package vegan (Oksanen *et al.* 2016). Detrended correspondence analysis was initially performed on the pollen data; however, the first-axis gradient length of 1.1483 suggests a linear response in the data set and therefore a principal component analysis (PCA) was performed. The PCA was performed on Hellinger-transformed data consisting of terrestrial pollen taxa with percentages >1%.

Core chronology

Samples were taken from the entire core to search for macrofossils for radiocarbon dating. Between the Hekla 5 tephra layer and the Saksunarvatn tephra *c.* 10 300 cal. a BP (Rasmussen *et al.* 2006) (190–260 cm), the core was systematically sampled at every centimetre for macrofossils as no marker tephras are found from this period in North Iceland. Eight macrofossil samples were sent for radiocarbon dating (Fig. 2, Table 1). The radiocarbon dates were calibrated to calendar years BP using the R package Clam (Blaauw 2010) and IntCal13 (Reimer *et al.* 2013). A smooth-spline model (Fig. 2) was constructed from Clam (Blaauw 2010), using 10 000 iterations and a smoothing of 0.13. Ages are given in calibrated years before present (cal. a BP; with the present assigned to AD 1950).

A new date for the Hekla 5 tephra layer was acquired by AMS radiocarbon dating of *Rhytidiadelphus squarrosus* mosses from Trjáviðarlækur in Þjórsárdalur valley, about 14 km NW of the Hekla volcano in south Iceland (Table 1). The mosses extracted from the moss–tephra boundary below the tephra layer were well preserved. The samples were wet sieved through a 125-μm mesh sieve and moss stems picked, cleaned of roots and other contaminants and sent for dating.

A previously undated tephra layer was found between the Hekla 4 (Dugmore *et al.* 1995) and Hekla Ö tephra layers (Gudmundsdóttir *et al.* 2011b). In this paper we refer to this tephra layer as HUN (abbreviation for Húnavatnssýsla). We have observed a tephra layer with a comparable geochemical composition and stratigraphical alignment in other places in Austur-Húnavatnssýsla, for example at Stóra-Bürfell, Kagaðarhóll (Eddudóttir *et al.* 2015) and Neðri Mýrar (Fig. 1; Table S1), where the tephra was found in a peat section. At Neðri Mýrar we took two wood samples that were in direct contact with the tephra. The species and biological age could not be confirmed but the samples came from the above-ground part of the plant (Ó. Eggertsson, pers. comm. 2015). The wood was cleaned of soil and roots and sent for radiocarbon dating (Table 1).

Tephra layers were identified visually, from changes in MS, DBD and OM and from X-ray images. Samples were washed through a 90-μm sieve and inspected in a stereomicroscope and samples consisting of mainly pristine volcanic glass shards were mounted on slides, polished and carbon coated. Major element analyses were performed at the University of Iceland using a JEOL JXA-8230 electron probe microanalyser. For most analyses acceleration voltage was 15 kV, beam current 10-nA and beam diameter 10 μm. For silicic, small-grained and highly crystallized tephra assemblages further analyses were performed using a 5 nA beam current and 5 μm beam diameter. To verify consistency in analytical conditions the standard A99 was

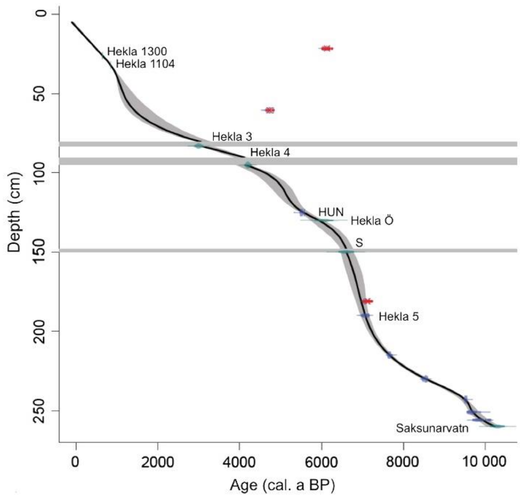

Fig. 2. Age-depth model for the Barðalækjartjörn core. Blue symbols indicate radiocarbon dates and new dates for tephra layers Hekla 5 and HUN (Table 1). Green symbols represent previously dated tephra layers and red symbols denote radiocarbon dates omitted from the age model. The grey area represents the 95% confidence interval; the black line shows the best fit of the model. Horizontal grey lines show tephra layers 2 cm or thicker. [Colour figure can be viewed at wileyonlinelibrary.com]

Table 1. Radiocarbon-dated macrofossil samples used in the age-depth model for the Barðalækjartjörn core.

Lab. code	Depth (cm)	^{14}C date (a BP)	Error 1σ	$\delta^{13}C$	Calibrated age (cal. a BP) 2σ error	Weight (mg)	Material
ETH-61948	21.5	5343	34	−29.2	6002–6266	0.31	Poaceae leaf fragments
ETH-61949	60.5	4188	27	−28.7	4627–4836	0.93	Miscellaneous mosses
ETH-61950	181.5	6207	29	−15.9	7006–7238	0.99	*Potamogeton* leaf fragments
ETH-61951	214.5	6836	30	−11.9	7608–7722	0.69	*Potamogeton* leaf fragments
ETH-61952	229.5	7753	31	−13.6	8453–8592	0.99	*Potamogeton* leaf fragments
ETH-61953	242.5	8551	35	−29.9	9489–9549	1.00	Miscellaneous mosses
ETH-61954	250.5	8714	35	−30.8	9549–9882	1.00	Miscellaneous mosses
ETH-61955	255.5	8818	35	−31.6	9697–10 135	0.99	Miscellaneous mosses
ETH-61956	190	6158	32	−28.0	6968–7162	0.96	*Rhytidiadelphus squarrosus* mosses Trjáviðarlækur (Hekla 5)
ETH-61925	125	4782	27	−27.1	5471–5589	0.99	Wood (unknown) – Neðri Mýrar (HUN tephra)
ETH-61926	125	4781	27	−27.5	5471–5589	1.00	Wood (unknown) – Neðri Mýrar (HUN tephra)

measured before and after each session of analysis. The data set was inspected for, and cleaned of, anomalies and analyses with sums of <97% (Table S1).

The core chronology (Fig. 2) is based on a combination of seven previously dated tephra layers, two new dates for tephra layers found in the core and five radiocarbon-dated macrofossil samples. Three samples of *Potamogeton* leaf fragments (at 181.5, 214.5 and 229.5 cm), four samples of miscellaneous mosses (at 60.5, 242.5, 250.5 and 255.5 cm) and one piece of a Poaceae leaf (at 21.5 cm) were dated. A sample of *Potamogeton* leaf fragments from 181.5 cm depth was slightly older than the Hekla 5 tephra 8.5 cm below it and was omitted from the model, as including the date would have caused an age reversal in the model. It should however be noted that the date falls within the 95% confidence interval of the age-depth model (Fig. 2, Table 1). The two uppermost dates proved much older than expected compared to the well-established tephrochronology of North Iceland (Larsen & Thorarinsson 1977; Eiríksson *et al.* 2000; Gudmundsdóttir *et al.* 2011a, b, 2012) and were therefore omitted. A possible explanation for older dates at these depths is old carbon being deposited in the lake due to soil erosion, which is common in Icelandic post-settlement sediments (e.g. Gathorne-Hardy *et al.* 2009).

The radiocarbon date for Hekla 5 from Trjáviðarlækur yielded a calibrated age of 7063±102 cal. a BP, similar to a previous date obtained by Thorarinsson (1971) of 7055±255 cal. a BP (2σ error for calibrated dates). The two radiocarbon samples for the HUN tephra from Neðri Mýrar both have the same calibrated age of 5530±59 (Table 1).

The following tephra layers were included in the model: Hekla 1300 (Larsen *et al.* 2002), Hekla 1104 (Þórarinsson 1967), Hekla 3 (3000 cal. a BP), Hekla 4 (4200 cal. a BP; Dugmore *et al.* 1995), HUN (Table 1), Hekla Ö (6060 cal. a BP; Gudmundsdóttir *et al.* 2011b), Katla S-layer (Eddudóttir *et al.* 2015), Hekla 5 (Table 1) and Saksunarvatn (10 300 cal. a BP; Rasmussen *et al.* 2006).

Results

Pollen and plant macrofossils

The Barðalækjartjörn vegetation record is shown in Figs 3–6. Percentages of Cyperaceae and *Betula* pollen are relatively high earlier in the record, and several types of pollen from herbs are recorded in PZ1. Increasing *Betula* percentages, PAR and larger *Betula* pollen diameters (Fig. 7) are accompanied by an absence of *Betula nana* macrofossils and an increase in *Betula* pollen diameters in PZ2. Herbs become more important in PZ3 as the *Betula* PAR decreases. In PZ4 Cyperaceae pollen increase and *Betula* pollen decrease whereas *Betula nana* and *Empetrum nigrum* macrofossils reappear. After 1000 cal. a BP, there is a further decrease in *Betula* pollen.

Principal component analysis

PCA axis 1 and axis 2 accounted for 53 and 16%, respectively, of the variability in the pollen dataset. The PCA (Fig. 8) shows indicators of open landscape, with *Thalictrum alpinum* and *Empetrum nigrum* prominent at the beginning of the record and an increase in *Juniperus communis*, a plant able to grow on free-draining soils and in harsh environments (García *et al.* 2000), within PZ1. *Betula* becomes the dominant taxa in PZ2. PCA axis 1 shows a trend from a closed canopy in PZ2, with an assemblage dominated by *Betula* (to the right along axis 1), towards a more open landscape in PZ3. The importance of heath and wetland habitats in the pollen assemblage are represented by *Vaccinium* and Cyperaceae (to the left along axis 1) in PZ4.

Lithology

MS values and DBD show a similar trend throughout the record and decrease from the beginning of the record with a period of relatively low values between 9100 and 8900 cal. BP (Fig. 6). DBD decreases from ~1.5 g cm^{-3} at the beginning of the record to <0.2 g cm^{-3} *c.* 8000 cal. a BP. Following the deposition of the Hekla 4 tephra layer DBD increases to ~0.20–0.25 g cm^{-3} and again to >0.33 g cm^{-3} after *c.* 1000 cal. a BP (Fig. 6). OM and %TC are highest in PZ2, up to 49 and 28%, respectively (Fig. 6). OM decreases following the thick Hekla 3 and Hekla 4 tephra layers to values of ~20–37% and to <20% after *c.* 1000 cal. a BP %TC decreases to <10% after *c.* 1000 cal a BP. The relatively high C/N ratios (between 10 and 19) recorded in the Barðalækjartjörn sediments show that terrestrial organic matter was an important component of the sediments throughout the record (Meyers & Lallier-Vergès 1999). The lowest C/N values are recorded between *c.* 7700 and 5400 cal. a BP (Fig. 6).

Holocene environmental dynamics at Barðalækjartjörn

Dwarf shrub heath c. 10 300 to 8000 cal. a BP

The vegetation assemblages represented in the pollen and macrofossil data from Barðalækjartjörn show that the Saksunarvatn tephra (*c.* 10 300 cal. a BP; Rasmussen *et al.* 2006) probably fell on land that was vegetated or at least partially so. This is suggested by the presence of dwarf shrubs such as *Betula nana* and *Salix* sp. immediately above the tephra, and the relatively low occurrence of pioneer species such as grasses and herbs, characteristic of young moraines and proglacial plains in Iceland today (Persson 1964; Vilmundardóttir *et al.* 2014, 2015a, b). The pollen and macrofossil records suggest that the vegetation around the lake was a combination of *Betula nana–Salix* sp.–*Juniperus communis* dwarf shrub heath, wetlands and rocky/sandy surfaces. Local presence of *Betula nana* is indicated by macrofossils (Fig. 5), and a mean *Betula* pollen grain diameter of ~18 μm (Fig. 6), consistent with modern *Betula nana* pollen (Mäkelä 1996). Willow dwarf shrubs are represented by *Salix herbacea*, *S. lanata* and *S. phylicifolia* macrofossils during this period. Additional indicators of heathland are *Selaginella selaginoides* spores and megaspores (Figs 3, 5) and *Rhodiola rosea* pollen (Fig. 3) (Kristinsson 2010). Occasional *Betula pubescens* fruits are recorded from

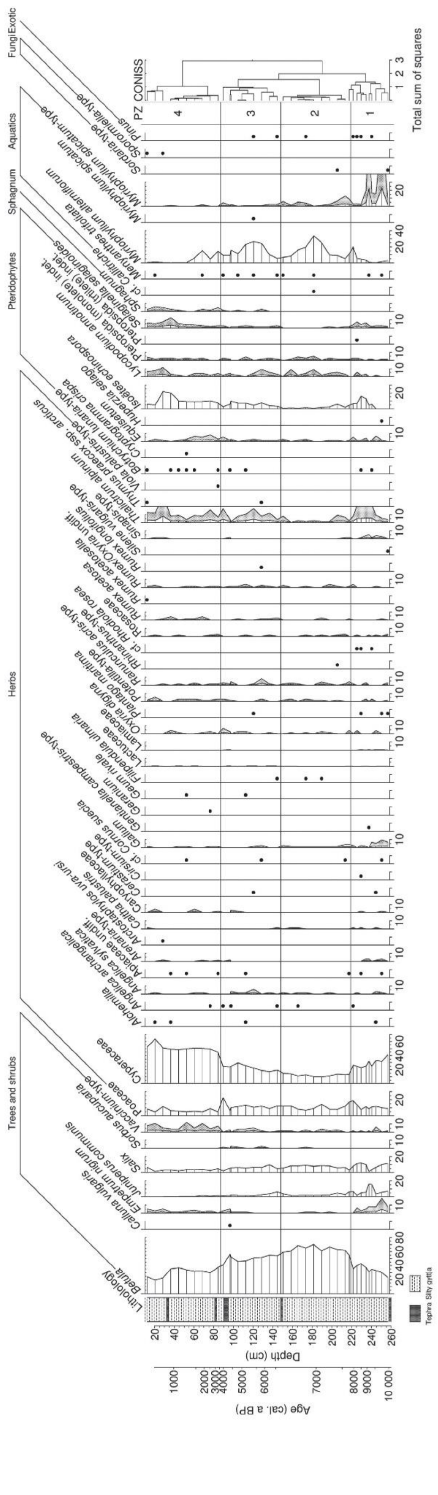

Fig. 3. Pollen percentage diagram from Lake Barðalækjartjörn. Exaggeration curves of factor 4. Dots signify percentages below 1%. The lithology column shows dated tephra layers used in the age-depth model.

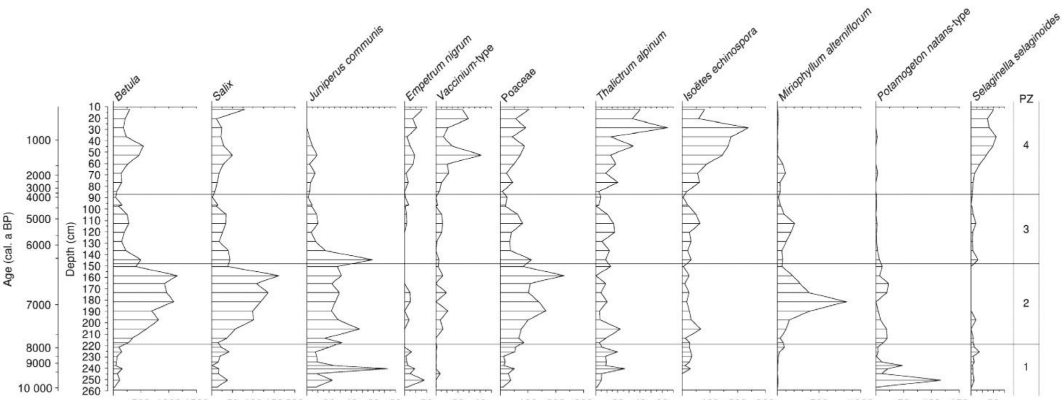

Fig. 4. Pollen accumulation rate (PAR, grains cm^{-2} a^{-1}) from Lake Barðalækjartjörn for selected taxa.

c. 10 000 cal. a BP, 700 years earlier than in the lowlands north of Barðalækjartjörn (Eddudóttir *et al.* 2015). *Betula pubescens* catkin scales are recorded after *c.* 8400 cal. a BP (Fig. 5). These macrofossils may be derived from scattered *Betula pubescens* individuals growing in the vicinity of the lake. The presence of *Angelica sylvatica* pollen (Fig. 3) suggests fully vegetated land near the lake and relatively warm conditions (Kristinsson 2010). Wetland habitats of the lake margins and/or of the wider landscape surrounding the lake are evidenced by fruits of wetland sedges (e.g. *Carex nigra*), *Sphagnum* moss leaves (Fig. 4) and pollen of wetland species *Caltha palustris* and *Menyanthes trifoliata* (Fig. 3). Sparsely vegetated surfaces near the lake are indicated by *Arenaria*-type (cf. *Arenaria norvegica* and/or *Minuartia rubella*) and *Plantago maritima* pollen (Fig. 3; Kristinsson 2010).

Harsh environmental conditions during this period are reflected in the high influx of minerogenic material recorded by MS and DBD until *c.* 8500 cal. a BP (Fig. 6), indicating substantial input of minerogenic material into the lake. A brief period between *c.* 9100 and 8900 cal. a BP of lower DBD and MS values (Fig. 6) suggests development towards a more stable landscape at a time of warm but variable climate (Langdon *et al.* 2010) and woodland development in North Iceland (Hallsdóttir 1995; Caseldine *et al.* 2006; Eddudóttir *et al.* 2015).

Aeolian processes probably influenced vegetation development around Barðalækjartjörn during the early Holocene until *c.* 8000 cal. a BP. Aeolian material was probably readily available as glaciers retreated and after the deposition of the Saksunarvatn tephra (eruption materials >15 km^3; Jóhannesdóttir *et al.* 2005).

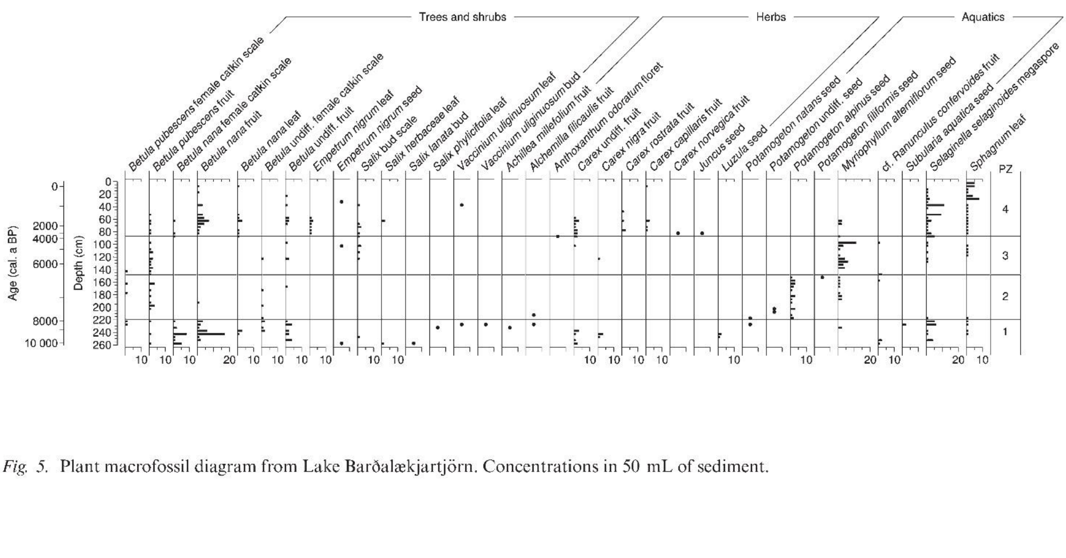

Fig. 5. Plant macrofossil diagram from Lake Barðalækjartjörn. Concentrations in 50 mL of sediment.

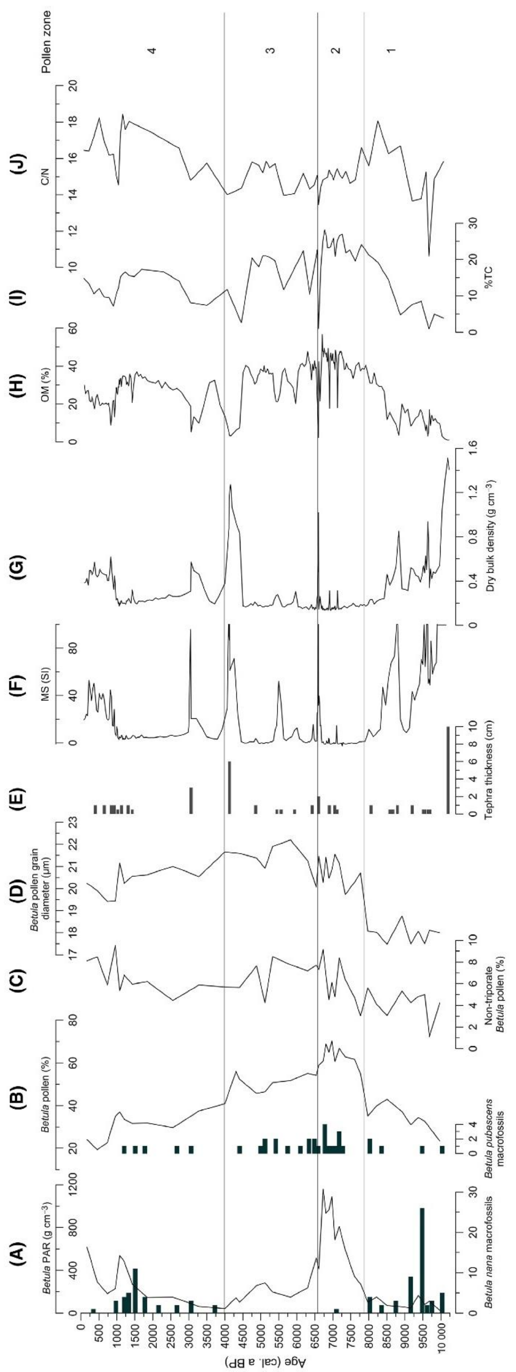

Fig. 6. Summary diagram for Lake Barðalækjartjörn showing (A) *Betula* pollen accumulation rate (PAR) (line) and *Betula nana* macrofossil occurrence in 50 mL of sediment (bars), (B) percentage of *Betula* pollen (line) and *Betula pubescens* macrofossil occurrence in 50 mL of sediment (bars), (C) percentage of non-triporate *Betula* pollen, (D) *Betula* pollen grain diameter, (E) tephra thickness (cm), (F) magnetic susceptibility (MS) showing values below 100, (G) dry bulk density (DBD), (H) organic matter (OM; measured by loss on ignition), (I) %Carbon, (J) C/N ratio. [Colour figure can be viewed at wileyonlinelibrary.com]

The influence of aeolian processes is seen in the prominence of species in the vegetation assemblage that are tolerant of aeolian deposits of 10 cm or less, such as *Betula nana*, *Salix herbacea*, *S. lanata* and *Thalictrum alpinum*. In addition, there is a low occurrence of dwarf shrubs that are sensitive to aeolian deposition, such as *Empetrum nigrum* and *Vaccinium uliginosum* (Vilmundardóttir *et al.* 2009). *Juniperus communis* is important in the pollen assemblage (Fig. 8), especially for the latter part of this period. This may suggest that soil conditions influenced the vegetation assemblage at the time (García *et al.* 2000).

After *c.* 8500–8000 cal. a BP a transition towards a more stable environment is seen from the DBD and MS data, accompanied by an increase in OM and %TC deposition. Despite *c.* 8700–8000 cal. a BP having been identified as a period of cool springs and summers in Northwest and west Iceland (Larsen *et al.* 2012; Geirsdóttir *et al.* 2013; Eddudóttir *et al.* 2015), little change is seen in the vegetation record. This is probably due to the resilience of the established dwarf shrub heath ecosystem. A further step towards a stable environment is reached *c.* 8000 cal. a BP, as values of DBD and MS become very low and OM and %TC increase further. This coincides with the beginning of the Holocene Thermal Maximum (HTM), a warm, stable period in Iceland (Caseldine *et al.* 2006; Langdon *et al.* 2010; Larsen *et al.* 2012; Geirsdóttir *et al.* 2013). Maximum distribution of woodlands in North Iceland occurred after *c.* 8000 cal. a BP (Hallsdóttir 1995; Wastl *et al.* 2001; Caseldine *et al.* 2006; Eddudóttir *et al.* 2015).

Stable woodland c. 8000 to 6700 cal. a BP

A transition from a *Betula nana*-dominated dwarf shrub heath to *Betula pubescens* woodland occurs after *c.* 8000 cal. a BP. *Betula* pollen increase (Figs 3, 8), and *Betula nana* macrofossils almost disappear entirely from the record (Figs 5, 6). Mean *Betula* pollen grain diameters increase to ~21 µm around 7800 cal. a BP (Figs 6, 7), comparable with measured mean diameters for *Betula pubescens* ssp. *tortuosa* (Mäkelä 1996). Optimum conditions for *Betula* pollen deposition occurred between *c.* 7400 and 6500 cal. a BP, with a maximum of ~900–1000 grains cm^{-2} a^{-1} between *c.* 7000 and 6700 cal. a BP (Figs 4, 6). This may indicate open birch woodland in the vicinity of the lake (Hicks 2001).

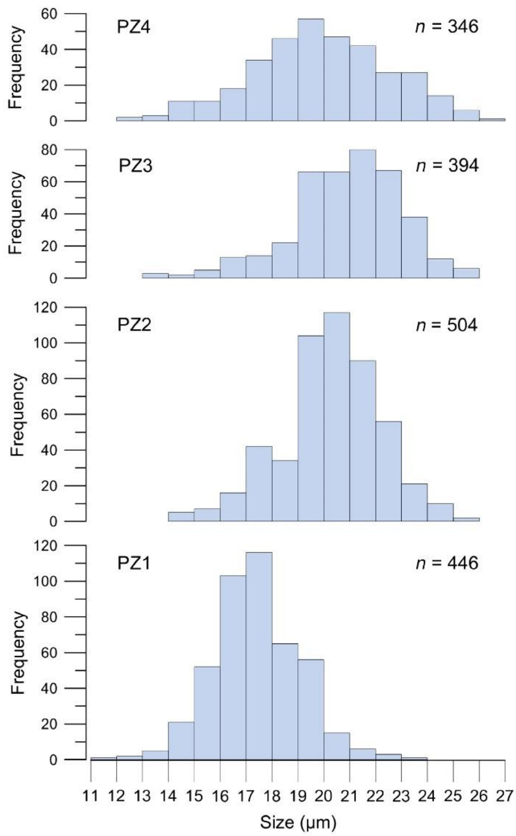

Fig. 7. Measured diameters (μm) of *Betula* pollen grains for each pollen zone. [Colour figure can be viewed at wileyonlinelibrary.com]

Non-triporate *Betula* pollen grains increase to ~9% (Fig. 6), probably due to increased hybridization between *Betula nana* and *B. pubescens* as *B. pubescens* colonized land previously occupied by *B. nana* (Karlsdóttir *et al.* 2008, 2009, 2012; Karlsdóttir 2014).

After a shift to larger *Betula* pollen diameters *c.* 7800 cal. a BP, the *Betula* PAR remains low for about 400 years, indicating that even though *Betula pubescens* was present around the lake, pollen was not deposited in large quantities, perhaps due to inhospitable environmental conditions for pollen production. At this time Barðalækjartjörn may have been located at the altitudinal limit of *Betula pubescens,* where pollen production is more sensitive to temperature than in closed woodlands (Kuoppamaa *et al.* 2009). This causes suppressed birch pollen production even though woodlands are present (Birks & Bjune 2010). Today in Iceland, birch flourishes when tritherm temperatures are above 9.2 °C (Jónsson 2005). Therefore the peak in *Betula* PAR between *c.* 7000 and 6700 cal. a BP may represent a short period of tritherm temperatures >9.2 °C at Barðalækjartjörn. Low DBD and MS and relatively high OM and %TC after *c.* 8000 cal. a BP and throughout the period are indicators of stability. Decreased C/N ratio by *c.* 7600 cal. a BP (Fig. 6) probably reflects increased importance of autochthonous organic material deposition as aquatic productivity increased (Meyers & Lallier-Vergès 1999). The environmental stability reflected in these records may suggest that the highlands in the vicinity of the lake were fully vegetated at the time.

The timing of the birch maximum (7400–6500 cal. a BP) at Barðalækjartjörn (413 m a.s.l.) coincides roughly with a birch maximum at 400–450 m a.s.l. on Tröllaskagi peninsula, North Iceland *c.* 7600–6800 cal. a BP (Wastl *et al.* 2001). The records show a similar delay in birch colonization of higher grounds despite apparently favourable climate conditions. A possible explanation for the apparent delay in birch woodland development at the highland margin compared with lowlands in North Iceland (Hallsdóttir 1995; Wastl *et al.* 2001; Caseldine *et al.* 2006; Eddudóttir *et al.* 2015) could be limited shelter from winds and continuous abrasion by aeolian material to which *Betula pubescens* is sensitive (Anderson *et al.* 1966; Elkington & Jones 1974).

Retreating woodland c. 6700 to 4000 cal. a BP

Opening of the woodland is seen from *c.* 6700 cal. a BP when the *Betula* PAR decreases to <900 grains cm^{-2} a^{-1} and *Betula* percentages fall below 60% (Figs 3, 4, 6). This sudden decrease in *Betula* PAR (Figs 4, 6) may be due to a change to lower summer temperatures and a shift in the altitudinal limit of birch to lower altitudes. Macrofossils of *Betula pubescens* are continuously recorded (Fig. 5) and *Betula* pollen diam-

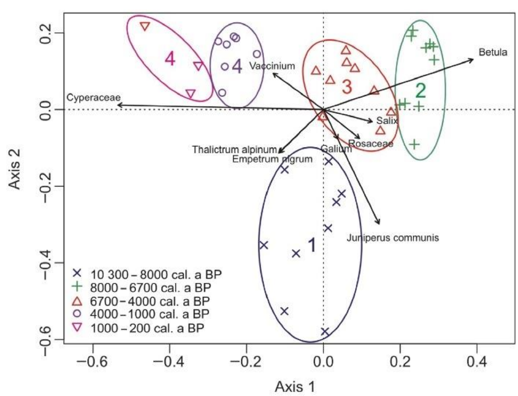

Fig. 8. Principal component analysis of the Barðalækjartjörn pollen data. Pollen samples divided by pollen zone. Pollen types clustered around the origin were removed for clarity. [Colour figure can be viewed at wileyonlinelibrary.com]

eters remain relatively large (~21 μm; Fig. 6). *Sorbus aucuparia* pollen are recorded regularly from *c.* 5800 cal. a BP (Fig. 3), which may reflect opening of woodlands (Hallsdóttir 1995). Increased presence of pollen of the herb *Thalictrum alpinum* from *c.* 6600 cal. a BP and *Selaginella selaginoides* spores by *c.* 6500 cal. a BP (Figs 3, 4) are additional indicators of opening woodland.

The environment is relatively stable during this period, and most fluctuations in DBD, MS and OM between *c.* 6700 and 5500 cal. a BP coincide with tephra layers in the sediment (Fig. 6). A further change towards dwarf shrub heath is seen after *c.* 5300 cal. a BP with an increase in *Vaccinium*-type pollen, and the reappearance of *Empetrum nigrum* pollen in the record by *c.* 5100 cal. a BP (Fig. 3). This change coincides with an increase in C/N ratios after *c.* 5300 cal. a BP (Fig. 6), probably a result of increased terrestrial input into the lake or lower aquatic productivity (Meyers & Lallier-Vergès 1999). This change in habitat and carbon deposition occurred at a time of cooling climate (Larsen *et al.* 2012; Geirsdóttir *et al.* 2013; Blair *et al.* 2015) and recorded glacier advances (Dugmore 1989; Dugmore & Sugden 1991; Kirkbride & Dugmore 2006).

Dwarf shrub heath c. 4000 to 1000 cal. a BP

Further development from woodland to dwarf shrub heath is seen above the Hekla 4 tephra layer (*c.* 4200 cal. a BP; Dugmore *et al.* 1995) when *Betula nana* and *Empetrum nigrum* macrofossils reappear in the record (Fig. 5). Mean *Betula* pollen diameters remain ~21 μm during this period, although the size distribution of the pollen grains has a wider range than before (Fig. 7). This implies that pollen from both *Betula nana* and *Betula pubescens* pollen were deposited in the lake. *Betula pubescens* fruits are recorded until *c.* 1200 cal. a BP (Fig. 5), showing a sustained presence of *Betula pubescens* in the local or regional vegetation. Stands of *B. pubescens* trees or shrubs may have grown amongst the dwarf shrub heath or, less likely, it is possible *Betula* pollen and *B. pubescens* macrofossils originated from further away through long-distance transport. The pollen assemblages finally shifted from woodland to heathland after *c.* 4000 cal. a BP, as *Vaccinium* and Cyperaceae pollen grew in importance (Figs 3, 8). Increases in both the percentages and PAR of Cyperaceae are accompanied by fruits of the wetland species *Carex rostrata*, as well as *C. capillaris* (Fig. 5). The increase in such moisture-loving taxa indicates an expansion of wetland habitats around the lake.

Instability following the deposition of the Hekla 4 tephra until the deposition of the Hekla 3 tephra *c.* 3000 cal. a BP (Dugmore *et al.* 1995) is evidenced by elevated MS and DBD values (Fig. 6). Higher values of MS and DBD *c.* 3000–1000 cal. a BP compared to before *c.* 4200 cal. a BP suggest that the environment was unable to recover to the more stable conditions before Hekla 4. After *c.* 3000 cal. a BP, OM and %TC decrease and the C/N ratio increases. This may either represent a further decrease in aquatic productivity as climate cooled, or an increase in organic sediment input of terrestrial origin (Fig. 6; Meyers & Lallier-Vergès 1999) due to increased soil erosion. Soil erosion may lead to reworking of older carbon (Gathorne-Hardy *et al.* 2009; Gísladóttir *et al.* 2010, 2011), which may influence measurements of C/N values. The source of minerogenic material deposited in the lake may be reworked tephra from the two Hekla eruptions, Hekla 3 and Hekla 4 (Larsen & Thorarinsson 1977), and/or loose material generated by increased glacier activity in the highlands in response to cooling climate (Kirkbride & Dugmore 2006; Geirsdóttir *et al.* 2009, 2013; Larsen *et al.* 2012; Striberger *et al.* 2012).

The effects of land use on the environment after c. 1000 cal. a BP

Birch probably disappeared from the surroundings of the lake *c.* 1000 cal. a BP. A final step towards *Betula nana*-dominated dwarf shrub heath is seen from a decrease in mean *Betula* pollen diameters to ~20 μm (Fig. 6) and a percentage decrease to ~20% after *c.* 1000 cal. a BP (Fig. 3). *Betula pubescens* macrofossils disappear at *c.* 1200 cal. a BP (Fig. 5). This probably signals the introduction of new environmental processes brought on by human activities and grazing, seen island wide at this time (Streeter *et al.* 2015). Given that this change takes place during a relatively warm period (the Medieval Warm Period, MWP; Eiríksson *et al.* 2000; Ogilvie & Jónsson 2001; Larsen *et al.* 2012), human activity is the most probable reason for this change. The decrease in *Betula c.* 1200–1000 cal. a BP and the disappearance of *Juniperus communis* pollen from the record by *c.* 1000 cal. a BP are probably a result of grazing in an environment where reproductive potential is undermined by unfavourable climate and an unstable landscape. Further indications of grazing by *c.* 700 cal. a BP are occurrences of spores of *Sporormiella*-type fungi (Fig. 3), which grow on dung from grazing herbivores (Cugny *et al.* 2010). Increased erosion is seen from *c.* 1000 cal. a BP when MS and DBD values increase with a corresponding drop in OM and %TC (Fig. 6), demonstrating significantly increased deposition of minerogenic material. The results from Barðalækjartjörn show that the effects of settlement on the highlands were similar in North and South Iceland. In South Iceland soil erosion began in upland areas >300 m a.s.l. immediately following settlement (Dugmore *et al.* 2009; Streeter & Dugmore 2014; Streeter *et al.* 2015). The location of Barðalækjartjörn at the highland margin and in the rangelands of Auðkúluheiði, as well as its small size allows the increase in local soil erosion to be recorded immediately. In contrast, large lakes with large high-altitude catchment areas like the lakes Haukadalsvatn and Hvítárvatn show no or limited response to settlement (Geirsdóttir *et al.* 2009, 2013; Larsen *et al.* 2012). This may be due to the significant background signal inherent in those records, in which signs of onset of local erosion may be overshadowed.

Introduction of woodcutting and grazing livestock reduced ecosystem resilience to cooling climate and volcanism. The added strain on an environment already under stress from cooling climate and large-scale tephra deposition undermined any potential for ecosystem recovery during the MWP. As a result, the capacity of the ecosystem to withstand further grazing, tephra deposition and the harsh conditions of the Little Ice Age (LIA) was diminished. The large-scale removal of woodland from both lowland and highland ecosystems and subsequent soil exposure during the MWP allowed soil erosion to escalate during the LIA (Streeter *et al.* 2015). The temporal pattern of post-settlement land degradation in both highland and lowland contexts emphasizes the importance of land use as a primary factor behind the exposed and eroded environment of the present day in Iceland.

Conclusions

The Barðalækjartjörn record reveals the dynamism of the Icelandic highland environment, where complex interactions of climate and human influence have shaped and changed the environment to varying degrees during the Holocene.

The earliest record suggests that the vegetation around the lake had already developed from the pioneer stage to a community of shrub heath. The shrub vegetation was able to withstand and to some extent contain the Saksunarvatn tephra deposits, which underscores the importance of tall vegetation cover for landscape stability in the wake of large tephra falls. Although the vegetation around Barðalækjartjörn withstood the tephra to some extent, loose sediments available for aeolian transport in the early Holocene influenced environmental stability and vegetation development for the following two millennia.

Birch woodland established late around Barðalækjartjörn in comparison with lowlands in North Iceland (Hallsdóttir 1987; Caseldine *et al.* 2006; Eddudóttir *et al.* 2015). In this windy environment the movement and abrasion of loose deposits may have prevented successful birch woodland establishment during the early Holocene, even though temperature requirements were perhaps fulfilled. This environmentally enforced delay extended into the period of cool climate between *c.* 8700 and 8000 cal. a BP, during which birch encroachment to higher altitudes was prevented by climate. After *c.* 7800 cal. a BP the necessary stability and temperatures were reached to allow birch woodland to develop at the highland margin and possibly beyond. Lithological proxies and *Betula* PAR show that optimum conditions for birch woodland and landscape stability were in place between *c.* 7000 and 6700 cal. a BP. The environmental stability recorded at Barðalækjartjörn during this period may suggest that the highlands in the vicinity of the lake were fully vegetated at the time. Retreat of the birch woodland occurred after *c.* 6700 cal. a BP. Further destabilization of the landscape is evident after the Hekla 4 tephra around 4200 cal. a BP, as the climate regime of Neoglaciation is increasingly felt in the highland. The exact role of climate is difficult to determine, however as the landscape was also affected by significant deposition of tephra.

The adverse environmental consequences of human settlement are observed in reduced representation of birch macrofossils and pollen percentages and increased erosion, particularly after *c.* 1000 cal. a BP. Human influence must be the primary mechanism behind these processes, considering that the change takes place during a period when the ecosystem should have been in a phase of recovery. Through the removal of woodland and weakening of the vegetation cover, grazing undermined the capacity of the ecosystem to withstand further challenges, such as large-scale tephra deposition and the harsh climate of the LIA.

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References

Anderson, D., Cooke, R., Elkington, T. & Read, D. 1966: Studies on structure in plant communities: II. The structure of some dwarf-heath and birch-copse communities in Skjaldfannardalur, North-West Iceland. *Journal of Ecology 54*, 781–793.

Arnalds, Ó. 2015: *The Soils of Iceland.* 183 pp. Springer, Dordrecht.

Bengtsson, L. & Enell, M. 1986: Chemical analysis. *In* Berglund, B. E. (ed.): *Handbook of Holocene Palaeoecology and Palaeohydrology*, 423–451. John Wiley & Sons, Chichester.

Bennett, K. D. 2007: *Catalogue of pollen types.* http://www.chrono.qub.ac.uk/pollen/pc-intro.html (accessed 26.11.2014).

Berggren, G. 1969: *Atlas of Seeds and Small Fruits of Northwestern-European Plant Species (Sweden, Norway, Denmark, East Fennoscandia and Iceland) with Morphological Descriptions: Part 2*

Cyperaceae. 68 pp. Swedish Natural Science Research Council, Stockholm.

Birks, H. H. 2007: Plant macrofossils - introduction. *In* Elias, S. A. (ed.): *Encyclopedia of Quaternary Science*, 2266–2288. Elsevier, Amsterdam.

Birks, H. H. & Bjune, A. E. 2010: Can we detect a west Norwegian tree line from modern samples of plant remains and pollen? Results from the DOORMAT project. *Vegetation History and Archaeobotany 19*, 325–340.

Björck, S., Persson, T. & Kristersson, I. 1978: Comparison of two concentration methods for pollen in minerogenic sediments. *GFF 100*, 107–111.

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

Blair, C. L., Geirsdóttir, Á. & Miller, G. H. 2015: A high-resolution multi-proxy lake record of Holocene environmental change in southern Iceland. *Journal of Quaternary Science 30*, 281–292.

Brady, N. C. & Weil, R. R. 1996: *Elements of the Nature and Properties of Soils*. 606 pp. Pearson Prentice-Hall, Upper Saddle River.

Cappers, R. T. J., Bekker, R. M. & Jans, J. E. A. 2012: *Digitale Zadenatlas van Nederland*. 502 pp. Barkhuis & Groningen University Library, Groningen.

Caseldine, C., Geirsdóttir, Á. & Langdon, P. 2003: Efstadalsvatn–a multi-proxy study of a Holocene lacustrine sequence from NW Iceland. *Journal of Paleolimnology 30*, 55–73.

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*, 2314–2331.

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*, 391–408.

Dearing, J. 1994: *Environmental Magnetic Susceptibility using the Bartington MS2 System*. 54 pp. Chi Publishing, Kenilworth.

Dugmore, A. 1989: Tephrochronological studies of Holocene glacier fluctuations in south Iceland. *In* Oerlemans, J. (ed.): *Glacier Fluctuations and Climatic Change*, 37–55. Kluwer Academic Publishers, Dordrecht.

Dugmore, A. J. & Sugden, D. E. 1991: Do the anomalous fluctuations of Sólheimajökull reflect ice-divide migration? *Boreas 20*, 105–113.

Dugmore, A. J., Church, M. J., Buckland, P. C., Edwards, K. J., Lawson, I., McGovern, T. H., Panagiotakopulu, E., Simpson, I. A., Skidmore, P. & Sveinbjarnardóttir, G. 2005: The Norse landnám on the North Atlantic islands: an environmental impact assessment. *Polar Record 41*, 21–37.

Dugmore, A. J., Cook, G. T., Shore, J. S., Newton, A. J., Edwards, K. J. & Larsen, G. 1995: Radiocarbon dating tephra layers in Britain and Iceland. *Radiocarbon 37*, 379–388.

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*, 1–18.

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. *The Holocene 25*, 1437–1453.

Einarsson, T. 1961: *Pollenanalytische Untersuchungen zur spät und postglazialen Klimageschichte Islands*. 52 pp. Sonderveröffentlichungen des Geologischen Instituts der Universität Köln, Cologne.

Eiríksson, J., Knudsen, K. L., 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. *Journal of Quaternary Science 15*, 573–580.

Elkington, T. T. & Jones, B. M. G. 1974: Biomass and primary productivity of birch (*Betula pubescens* s. lat.) in South-West Greenland. *Journal of Ecology 62*, 821–830.

Erlendsson, E. 2007: *Environmental change around the time of the Norse settlement of Iceland*. Ph.D. thesis, University of Aberdeen, 301 pp.

Fægri,, K., Kaland, P. E. & Krzywinski, K. 1989: *Textbook of Pollen Analysis*. 328 pp. John Wiley & Sons, New York.

García, D., Zamora, R., Gómez, J. M., Jordano, P. & Hódar, J. A. 2000: Geographical variation in seed production, predation and abortion in *Juniperus communis* throughout its range in Europe. *Journal of Ecology 88*, 435–446.

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*, 413–426.

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*, 873–883.

Geirsdóttir, Á., Miller, G. H., Axford, Y. & Ólafsdóttir, S. 2009: Holocene and latest Pleistocene climate and glacier fluctuations in Iceland. *Quaternary Science Reviews 28*, 2107–2118.

Geirsdóttir, Á., Miller, G. H., Larsen, D. J. & Ólafsdóttir, S. 2013: Abrupt Holocene climate transitions in the northern North Atlantic region recorded by synchronized lacustrine records in Iceland. *Quaternary Science Reviews 70*, 48–62.

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*, 20–32.

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

Guðbergsson, G. 1996: Í norðlenskri vist. Um gróður, jarðveg, búskaparlög og sögu. *Búvísindi 10*, 31–89.

Gudmundsdóttir, E. R., Eiríksson, J. & Larsen, G. 2011a: Identification and definition of primary and reworked tephra in Late Glacial and Holocene marine shelf sediments off North Iceland. *Journal of Quaternary Science 26*, 589–602.

Gudmundsdóttir, E. R., Larsen, G. & Eiríksson, J. 2011b: Two new Icelandic tephra markers: the Hekla Ö tephra layer, 6060 cal. yr BP, and Hekla DH tephra layer, ~6650 cal. yr BP. Land-sea correlation of mid-Holocene tephra markers. *The Holocene 21*, 629–639.

Gudmundsdóttir, E. R., Larsen, G. & Eiríksson, J. 2012: Tephra stratigraphy on the North Icelandic shelf: extending tephrochronology into marine sediments off North Iceland. *Boreas 41*, 719–734.

Hallsdóttir, M. 1982: Frjógreining tveggja jarðvegssniða úr Hrafnkelsdal. Áhrif ábúðar á gróðurfar dalsins. *In* Þórarinsdóttir, H., Óskarsson, Ó. H., Steinþórsson, S. & Einarsson Þ. (eds.): *Eldur er í norðri*, 253–265. Sögufélag, Reykjavík.

Hallsdóttir, M. 1987: Pollen analytical studies of human influence on vegetation in relation to the Landnám tephra layer in southwest Iceland. *LUNDQUA Thesis 18*, 45 pp.

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., Russel, A., Harðardóttir, J. & Knudsen, Ó. (eds.): *Iceland – Modern Processes and Past Environments*, 319–334. Elsevier, Amsterdam.

Hicks, S. 2001: The use of annual arboreal pollen deposition values for delimiting tree-lines in the landscape and exploring models of pollen dispersal. *Review of Palaeobotany and Palynology 117*, 1–29.

Icelandic Met Office 2014: *Mánaðarmeðaltöll/Monthly data*. http://www.vedur.is/Medaltalstoflur-txt/Manadargildi.html (accessed 11.11.2014).

Jóhannesdóttir, G., Thordarson, T., Geirsdóttir, Á. & Larsen, G. 2005: The widespread ~10 ka Saksunarvatn tephra: a product of three large basaltic phreatoplinian eruptions. *European Geosciences Union, Geophysical Research Abstracts 7*, 05991.

Jónsdóttir, I. S., Magnússon, B., Gudmundsson, J., Elmarsdóttir, Á. & Hjartarson, H. 2005: Variable sensitivity of plant communities in Iceland to experimental warming. *Global Change Biology 11*, 553–563.

Jónsson, Þ. H. 2005: Útbreiðsla birkis á Íslandi. *Skógræktarritið 2*, 61–71.

Karlsdóttir, L. 2014: *Hybridisation of Icelandic birch in the Holocene reflected in pollen*. Ph.D. thesis, University of Iceland, 159 pp.

Karlsdóttir, L., Hallsdóttir, M., Thórsson, A. T. & Anamthawat-Jónsson, K. 2008: Characteristics of pollen from natural triploid *Betula* hybrids. *Grana 47*, 52–59.

Karlsdóttir, L., Hallsdóttir, M., Thórsson, Æ. T. & Anamthawat-Jónsson, K. 2009: Evidence of hybridisation between *Betula pubescens* and *B. nana* in Iceland during the early Holocene. *Review of Palaeobotany and Palynology 156*, 350–357.

Karlsdóttir, L., Hallsdóttir, M., Thórsson, Æ. T. & Anamthawat-Jónsson, K. 2012: Early Holocene hybridisation between *Betula pubescens* and *B. nana* in relation to birch vegetation in Southwest Iceland. *Review of Palaeobotany and Palynology 181*, 1–10.

Katz, N. J., Katz, S. V. & Kipiani, M. G. 1965: *Atlas and Keys of Fruits and Seeds Occurring in the Quaternary Deposits of the USSR*. 365 pp. Publishing House Nauka, Moscow.

Kirkbride, M. P. & Dugmore, A. J. 2006: Responses of mountain ice caps in central Iceland to Holocene climate change. *Quaternary Science Reviews 25*, 1692–1707.

Kristinsson, H. 2010: *Flowering Plants and Ferns of Iceland*. 364 pp. Mál og menning, 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 24*, 513–521.

Langdon, P. G., Leng, M., Holmes, N. & Caseldine, C. J. 2010: Lacustrine evidence of early-Holocene environmental change in northern Iceland: a multiproxy palaeoecology and stable isotope study. *The Holocene 20*, 205–214.

Larsen, G. & Eiriksson, J. 2008: Late Quaternary terrestrial tephrochronology of Iceland—frequency of explosive eruptions, type and volume of tephra deposits. *Journal of Quaternary Science 23*, 109–120.

Larsen, G. & Thorarinsson, S. 1977: H4 and other acid Hekla tephra layers. *Jökull 27*, 28–46.

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 Reviews 39*, 14–25.

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*, 283–290.

Magnússon, Á. & Vídalín, P. 1926: *Jarðabók Árna Magnússonar og Páls Vídalíns áttunda bindi*. 511 pp. Hið Íslenska Fræðafjelag Í, Kaupmannahöfn.

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

McGovern, T. H., Vésteinsson, O., Friðriksson, A., Church, M., Lawson, I., Simpson, I. A., Einarsson, A., Dugmore, A., Cook, G. & Perdikaris, S. 2007: Landscapes of settlement in northern Iceland: historical ecology of human impact and climate fluctuation on the millennial scale. *American Anthropologist 109*, 27–51.

Meyers, P. A. & Lallier-Vergès, E. 1999: Lacustrine sedimentary organic matter records of Late Quaternary paleoclimates. *Journal of Paleolimnology 21*, 345–372.

Moore, P. D., Webb, J. A. & Collison, M. E. 1991: *Pollen Analysis*. 216 pp. Blackwell Scientific Publications, Oxford.

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*, 15–24.

Ogilvie, A. E. J. & Jónsson, T. 2001: 'Little Ice Age' research: a perspective from Iceland. *Climatic Change 48*, 9–52.

Oksanen, J., Blanchet, F. G., Kindt, R., Legendre, P., Minchin, P. R., O'Hara, R. B., Simpson, G. L., Solymos, P., Stevens, M. H. H. & Wagner, H. 2016: *vegan: Community Ecology Package. R package version 2.3-3, URL.* https://cran.r-project.org/web/packages/vegan/

Persson, Å. 1964: The vegetation at the margin of the receding glacier Skaftafellsjökull, Southeastern Iceland. *Botaniska Notiser 117*, 323–354.

Þórarinsson, S. 1967: *The Eruption of Hekla 1947–48 I*. 183 pp. Societas Scientiarum Islandica, Reykjavík.

Rasmussen, S. O., Andersen, K. K., Svensson, A. M., Steffensen, J. P., Vinther, B. M., Clausen, H. B., Siggaard-Andersen, M. L., Johnsen, S. J., Larsen, L. B., Dahl-Jensen, D., Bigler, M., Röthlisberger, R., Fischer, H., Goto-Azuma, K., Hansson, M. E. & Ruth, U. 2006: A new Greenland ice core chronology for the last glacial termination. *Journal of Geophysical Research: Atmospheres 111*, D06102.

Reimer, P. J., Bard, E., Bayliss, A., Beck, J. W., Blackwell, P. G., Bronk Ramsey, C., Buck, C. E., Cheng, H., Edwards, R. L., Friedrich, M., Grootes, P. M., Guilderson, T. P., Haflidason, H., Hajdas, I., Hatte, C., Heaton, T. J., Hoffmann, D. L., Hogg, A. G., Hughen, K. A., Kaiser, K. F., Kromer, B., Manning, S. W., Niu, M., Reimer, R. W., Richards, D. A., Scott, E. M., Southon, J. R., Staff, R. A., Turney, C. S. M. & van der Plicht, J. 2013: IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. R. *Radiocarbon 55*, 1869–1887.

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

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

Streeter, R. & Dugmore, A. 2014: Late-Holocene land surface change in a coupled social–ecological system, southern Iceland: a cross-scale tephrochronology approach. *Quaternary Science Reviews 86*, 99–114.

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. *The Holocene 25*, 1662–1675.

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.

Thorarinsson, S. 1971: The age of the light Hekla tephra layers according to corrected C14–datings. *Náttúrufræðingurinn 41*, 99–105.

Thordarson, T. & Larsen, G. 2007: Volcanism in Iceland in historical time: volcano types, eruption styles and eruptive history. *Journal of Geodynamics 43*, 118–152.

Thórsson, Æ. T., Salmela, E. & Anamthawat-Jónsson, K. 2001: Morphological, cytogenetic, and molecular evidence for introgressive hybridization in birch. *Journal of Heredity 92*, 404–408.

Thórsson, 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*, 1183–1193.

Vésteinsson, O. & McGovern, T. H. 2012: The peopling of Iceland. *Norwegian Archaeological Review 45*, 206–218.

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. *The Holocene 21*, 979–995.

Vilmundardóttir, O. K., Gísladóttir, G. & Lal, R. 2014: Early stage development of selected soil properties along the proglacial moraines of Skaftafellsjökull glacier, SE-Iceland. *Catena 121*, 142–150.

Vilmundardóttir, O., Gísladóttir, G. & Lal, R. 2015a: Between ice and ocean; soil development along an age chronosequence formed by the retreating Breiðamerkurjökull glacier, SE-Iceland. *Geoderma 259*, 310–320.

Vilmundardóttir, O. K., Gísladóttir, G. & Lal, R. 2015b: Soil carbon accretion along an age chronosequence formed by the retreat of the Skaftafellsjökull glacier, SE-Iceland. *Geomorphology 228*, 124–133.

Vilmundardóttir, O. K., Magnússon, B., Gísladóttir, G. & Magnússon, S. M. 2009: Gróðurframvinda í áfoksgeira í mólendi við Blöndulón. *Náttúrufræðingurinn 78*, 125–137.

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 32*, 191–203.

Wöll, C. 2008: *Treeline of mountain birch (Betula pubescens Ehrh.) in Iceland and its relationship to temperature.* Diplom thesis, Technische Universität Dresden, Dresden, 124 pp.

Supporting Information

Additional Supporting Information may be found in the online version of this article at http://www.boreas.dk.

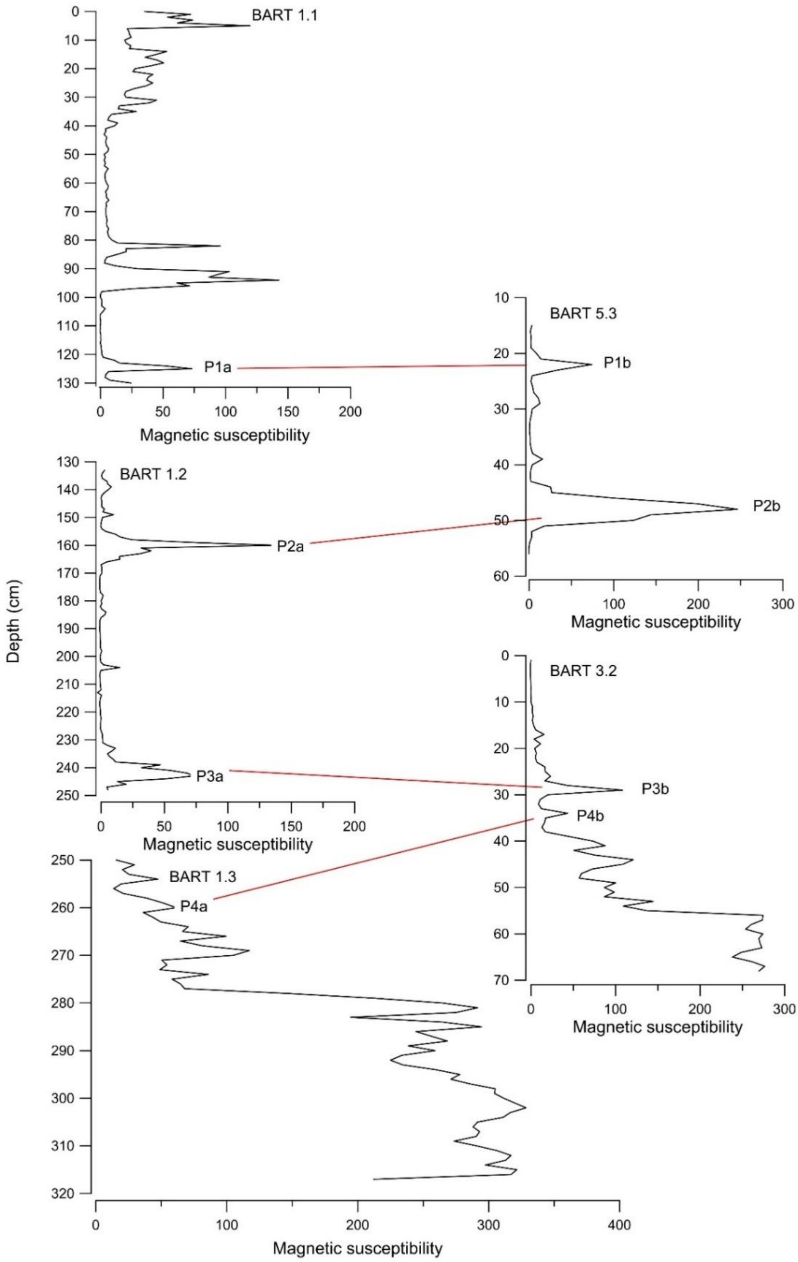
Fig. S1. Magnetic susceptibility measurements of overlapping core segments for the Barðalækjartjörn core succession.

Fig. S2. Geochemical analyses of tephra samples from overlapping cores. Values are wt%.

Fig. S3. Geochemical analyses of tephra layers found in the Barðalækjartjörn cores plotted against reference samples obtained from the literature. Values are wt%.

Table S1. Major element composition (wt%) of key tephra layers in the BART (Barðalækjartjörn) and NM (Neðri Mýrar) sequences.

Supplementary material



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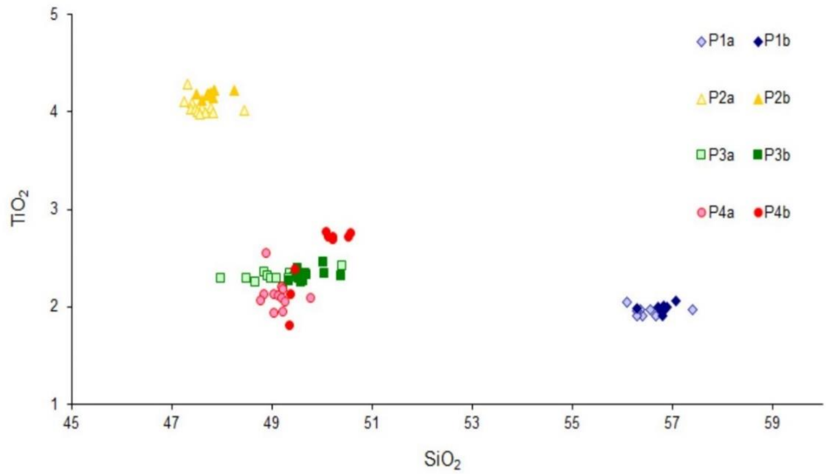

Fig. S2. Geochemical analyses of tephra samples from overlapping cores.

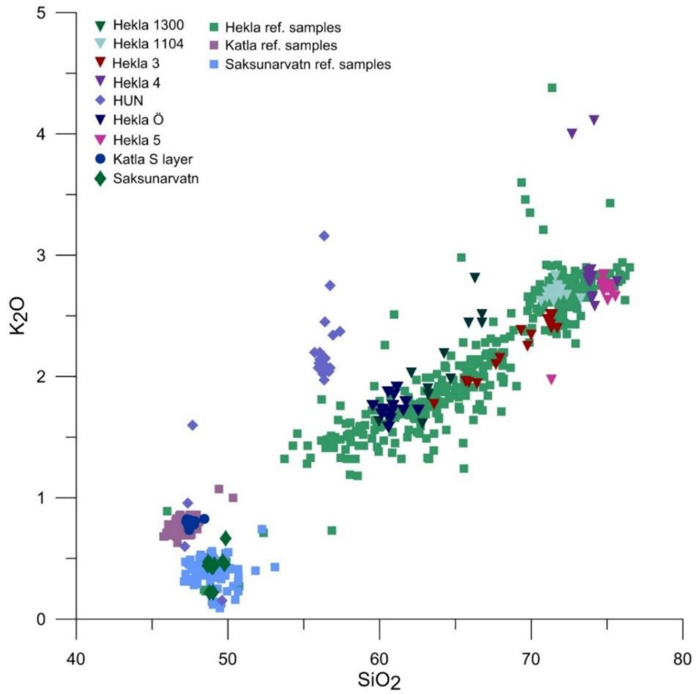

Fig. S3. Geochemical analyses of tephra layers found in the Barðalækjartjörn cores plotted against reference samples obtained from the literature. Hekla reference samples: (Dugmore & Newton 1992; Dugmore *et al.* 1992; Boygle 1995; Dugmore & Newton 1995; Pilcher *et al.* 1995; Pilcher & Hall 1996; Pilcher *et al.* 1996; Dugmore & Newton 1997; Larsen *et al.* 1999; Wastegård *et al.* 2001; Hall & Pilcher 2002; Zillén *et al.* 2002; Pilcher *et al.* 2005; Swindles 2006; Lawson *et al.* 2007; Gudmundsdóttir *et al.* 2011; Streeter & Dugmore 2014), Katla reference samples: (Streeter & Dugmore 2014) and Saksunarvatn reference samples (Mangerud *et al.* 1986; Bennett *et al.* 1992; Bunting 1994; Dugmore & Newton 1997; Wastegård *et al.* 2001; Andrews *et al.* 2002; Lloyd *et al.* 2009).

References

Andrews, J. T., Geirsdóttir, A., Hardardóttir, J., Principato, S., Grönvold, K., Kristjansdóttir, G. B., Helgadóttir, G., Drexler, J. & Sveinbjörnsdóttir, A. 2002: Distribution, sediment magnetism and geochemistry of the Saksunarvatn (10 180±60 cal. yr BP) tephra in marine, lake, and terrestrial sediments, northwest Iceland. *Journal of Quaternary Science 17*, 731-745.

Bennett, K., Boreham, S., Sharp, M. & Switsur, V. 1992: Holocene history of environment, vegetation and human settlement on Catta Ness, Lunnasting, Shetland. *Journal of Ecology*, 241-273.

Boygle, J. E. 1995: Tephra in lake sediments: an unambiguous geochronological marker? University of Edinburgh.

Bunting, M. 1994: Vegetation history of Orkney, Scotland; pollen records from two small basins in west Mainland. *New Phytologist 128*, 771-792.

Dugmore, A. & Newton, A. 1997: Holocene tephra layers in the Faroe Islands. *Frodskaparrit 45*, 141-154.

Dugmore, A. J. & Newton, A. J. 1992: Thin tephra layers in peat revealed by X-radiography. *Journal of Archaeological Science 19*, 163-170.

Dugmore, A. J. & Newton, A. J. 1995: Seven tephra isochrones in Scotland. *The Holocene 5*, 257-266.
Dugmore, A. J., Newton, A. J., Sugden, D. E. & Larsen, G. 1992: Geochemical stability of fine-grained silicic Holocene tephra in Iceland and Scotland. *Journal of Quaternary Science 7*, 173-183.
Gudmundsdóttir, E. R., Larsen, G. & Eiríksson, J. 2011: Two new Icelandic tephra markers: The Hekla Ö tephra layer, 6060 cal. yr BP, and Hekla DH tephra layer, ~6650 cal. yr BP. Land-sea correlation of mid-Holocene tephra markers. *The Holocene 21*, 629-639.
Hall, V. A. & Pilcher, J. R. 2002: Late-Quaternary Icelandic tephras in Ireland and Great Britain: detection, characterization and usefulness. *The Holocene 12*, 223-230.
Larsen, G., Dugmore, A. & Newton, A. 1999: Geochemistry of historical-age silicic tephras in Iceland. *The Holocene 9*, 463-471.
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*, 1-19.
Lloyd, J. M., Norðdahl, H., Bentley, M. J., Newton, A. J., Tucker, O. & Zong, Y. 2009: Lateglacial to Holocene relative sea-level changes in the Bjarkarlundur area near Reykhólar, North West Iceland. *Journal of Quaternary Science 24*, 816-831.
Mangerud, J., Furnes, H. & Jóhansen, J. 1986: A 9000-year-old ash bed on the Faroe Islands. *Quaternary Research 26*, 262-265.
Pilcher, J. R., Bradley, R. S., Francus, P. & Anderson, L. 2005: A Holocene tephra record from the Lofoten Islands, arctic Norway. *Boreas 34*, 136-156.
Pilcher, J. R. & Hall, V. A. 1996: Tephrochronological studies in northern England. *The Holocene 6*, 100-105.
Pilcher, J. R., Hall, V. A. & McCormac, F. G. 1995: Dates of Holocene Icelandic volcanic eruptions from tephra layers in Irish peats. *The Holocene 5*, 103-110.
Pilcher, J. R., Hall, V. A. & McCormac, F. G. 1996: An outline tephrochronology for the Holocene of the north of Ireland. *Journal of Quaternary Science 11*, 485-494.
Streeter, R. & Dugmore, A. 2014: Late-Holocene land surface change in a coupled social–ecological system, southern Iceland: a cross-scale tephrochronology approach. *Quaternary Science Reviews 86*, 99-114.
Swindles, G. 2006: Reconstruction of Holocene climate change from peatlands in the north of Ireland. *Geophysical Research Abstracts.* Queen's University, Belfast.
Wastegård, S., Björck, S., Grauert, M. & Hannon, G. E. 2001: The Mjáuvøtn tephra and other Holocene tephra horizons from the Faroe Islands: a link between the Icelandic source region, the Nordic Seas, and the European continent. *The Holocene 11*, 101-109.
Zillén, L. M., Wastegård, S. & Snowball, I. F. 2002: Calendar year ages of three mid-Holocene tephra layers identified in varved lake sediments in west central Sweden. *Quaternary Science Reviews 21*, 1583-1591

Table S1. Major element composition (wt%) of key tephra layers in the BART (Barðalækjartjörn) and NM (Neðri Mýrar) sequences.

Site	Depth (cm)	Av./SD	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	SUM	N/N total	Tephra
BART	25-26	Av.	63.87	0.85	14.69	7.32	0.22	0.77	3.92	4.42	2.09	0.38	98.53	12/12	Hekla 1300
		SD	2.31	0.22	1.50	1.11	0.03	0.27	0.83	0.45	0.39	0.13			
BART	31-32	Av.	71.64	0.21	14.10	3.21	0.12	0.11	1.85	3.93	2.69	0.03	97.90	18/18	Hekla 1104
		SD	0.56	0.02	0.15	0.05	0.02	0.01	0.08	0.81	0.05	0.02			
BART	82-83	Av.	69.23	0.30	14.56	4.28	0.15	0.26	2.52	4.16	2.26	0.06	97.78	17/17	Hekla 3
		SD	2.55	0.15	0.51	1.48	0.04	0.20	0.67	0.23	0.24	0.06			
BART	94-95	Av.	73.98	0.14	13.09	2.03	0.08	0.04	1.15	3.93	2.97	0.02	97.43	13/13	Hekla 4
		SD	0.63	0.09	0.18	0.10	0.02	0.05	0.31	0.45	0.49	0.02			
BART	124.5-125	Av.	56.38	1.98	15.44	9.49	0.18	2.63	5.76	4.30	2.23	0.39	98.76	19/23	HUN
		SD	0.39	0.05	0.17	0.33	0.03	0.08	0.23	0.22	0.29	0.04			
BART	130	Av.	60.86	1.05	14.27	9.99	0.28	1.31	4.43	4.21	1.75	0.48	98.61	14/23	Hekla Ö
		SD	0.74	0.06	0.38	0.49	0.02	0.08	0.18	0.18	0.09	0.05			
BART	148-150	Av.	47.60	4.05	13.04	14.62	0.23	5.19	9.77	2.93	0.79	0.51	98.74	12/12	Katla S
		SD	0.32	0.08	0.20	0.69	0.02	0.57	0.64	0.17	0.03	0.02			
BART	188-189	Av.	74.70	0.09	12.98	1.69	0.07	0.03	1.32	4.17	2.68	0.01	97.74	13/13	Hekla 5
		SD	1.06	0.02	0.87	0.13	0.02	0.01	0.30	0.44	0.22	0.01			
BART	256.5-257.5	Av.	49.14	2.91	13.01	14.15	0.25	5.49	9.82	2.66	0.47	0.34	98.24	10/12	Saksunarv.
		SD	0.45	0.09	0.19	0.18	0.01	0.14	0.14	0.11	0.07	0.03			
NM	91-92	Av.	56.69	2.05	15.56	9.88	0.19	2.67	5.83	4.26	1.95	0.40	99.48	6/9	HUN
		SD	0.22	0.06	0.18	0.32	0.02	0.07	0.22	0.66	0.44	0.04			

Paper III

Effects of the Hekla 4 tephra on vegetation in Northwest Iceland

Sigrún Dögg Eddudóttir[1], Egill Erlendsson[1] and Guðrún Gísladóttir[1,2]

Effects of the Hekla 4 tephra on vegetation in Northwest Iceland

[1]Institute of Life and Environmental Sciences, University of Iceland, Sturlugata 7, 101 Reykjavík, Iceland
[2]Institute of Earth Sciences, University of Iceland, Sturlugata 7, 101 Reykjavík, Iceland

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Abstract

Recent volcanic eruptions in Iceland have highlighted the consequences of tephra fall for ecosystems and human health. Improved understanding of the mechanisms behind ecosystem recovery following tephra fall is particularly important for Iceland where ~42 % of the country is classified as desert. Vegetation plays a key role in preventing remobilisation of tephra and aeolian activity following tephra fall. Unvegetated and sparsely vegetated areas are unable to trap tephra fall and prevent subsequent wind erosion. This paper presents palaeoenvironmental reconstructions before and after the Hekla 4 tephra from two lakes in Northwest Iceland, from within a woodland in the lowland and in open woodland under stress at the highland margin. The *c*. 4200 cal B.P. Hekla 4 tephra is one of the most extensive Icelandic Holocene tephra layers and the eruption produced an estimated ~9 $km^3$of tephra. The palaeoecological reconstructions provide an insight into the responses of two relatively stable ecosystems to thick tephra deposits during a period of cooling climate. The understory vegetation in the lowland woodland was buried by the tephra, however *Betula pubescens* trees were not severely affected and the woodland recovered relatively quickly. In contrast, open woodland at the highland margin that was already at its ecological limit, shifted to dwarf shrub heath, a more resilient vegetation community in response to the tephra fall and cooling climate.

Keywords: Tephra, vegetation, pollen, Iceland, Hekla, *Betula pubescens*

Introduction

Iceland is a volcanic hotspot due to its location on the mid-Atlantic plate boundary and above the Iceland mantle plume (Einarsson 2008). Volcanic eruptions have occurred on average every five years during the Holocene (Thordarson and Höskuldsson 2008), and eruption frequency may increase in the future due to warming climate (Sigmundsson et al. 2010). Volcanic systems such as Bárðarbunga, Katla and Hekla, known for producing large explosive eruptions (Thordarson and Höskuldsson 2008) currently show signs of increased activity (Larsen et al. 2015a, b, c). Recent eruptions, such as the 2010 eruption of Eyjafjallajökull and the 2011 Grímsvötn eruption have highlighted the consequences of tephra fall from volcanic activity for ecosystems and humans alike. These include health issues (Carlsen et al. 2012a, b) as tephra in the environment can cause an increase in eye, nose and respiratory problems (Horwell and Baxter 2006; Weinstein et al. 2013; Horwell et al. 2015), impact on farming communities (Thorvaldsdóttir and Sigbjörnsson 2015), and long term remobilisation of tephra following eruptions (Thorsteinsson et al. 2012; Arnalds et al. 2013, 2016).

Vegetation plays a key role in preventing remobilisation of tephra and aeolian activity following eruptions (Arnalds 2013a; Arnalds et al. 2013; Cutler et al. 2016). Improved knowledge of the mechanisms behind ecosystem recovery is particularly important in Iceland. The Icelandic terrestrial environment and vegetation have undergone great changes since human settlement due to land use (Dugmore et al. 2005, 2009; McGovern et al. 2007; Gathorne-Hardy et al. 2009; Gísladóttir et al. 2011; Vickers et al. 2011) and today about 43,000 km^2, or ~42 % of the country is classified as desert (Gísladóttir et al. 2014). Intensive land-use, cooling climate, volcanic activity and floods have contributed to this change (Arnalds 2015). Unvegetated and sparsely vegetated areas are unable to entrap tephra fall and prevent subsequent wind erosion and redeposition of tephra. Redistribution of tephra for long periods following eruptions poses a potentially significant problem in the wake of large explosive eruptions in Iceland (Thorsteinsson et al. 2012; Arnalds 2013a, b; Arnalds et al. 2013; Liu et al. 2014).

Heavy tephra falls from explosive eruptions have influenced the environment and people's livelihood since humans first settled Iceland *c.* A.D. 870. The A.D. 1104 eruption of Hekla (Hekla 1104) produced an estimated volume of ~2 km^3 of tephra (Larsen and Thorarinsson 1977) and is believed to have caused changes in land use patterns and perhaps permanent abandonment of farms in nearby Þjórsárdalur. Woodland in the valley survived the tephra deposition and vegetation grew through >35 cm thick deposits (Dugmore et al. 2007). The A.D. 1875 eruption of Askja in East Iceland produced ~1.83 km^3 of tephra (Carey et al. 2010) and contributed to abandonment of many upland farms (Thorarinsson 1944). The Öræfajökull eruption in Southeast Iceland in A.D. 1362 has long been considered the most catastrophic eruption in Icelandic history, possibly rendering the district of Litla-Hérað uninhabitable for some time after the eruption (Thorarinsson 1958). Estimates of the volume of tephra produced in the Öræfajökull eruption range from 2.3 km^3 (Sharma et al. 2008) to 10 km^3 (Thorarinsson 1958).

Two of the largest explosive eruptions of the Holocene in Iceland were produced by the Hekla volcanic system located at the edge of the Eastern Volcanic Zone in South Iceland. Volcanic activity in the Hekla volcanic system between *c*. 7000 and 3000 cal B.P. was mainly characterised by large explosive eruptions producing silicic and basaltic andesite tephra layers (Larsen et al. 2015c). The Hekla 3 eruption (~3000 cal B.P.; Dugmore et al. 1995) is estimated to have produced 12 km^3 and Hekla 4 (~4200 cal B.P.; Dugmore et al. 1995) 9 km^3 of freshly fallen tephra (Larsen and Thorarinsson 1977). Tephra from both eruptions covered most of the country although the largest volumes of tephra were carried north and northeast (Fig. 1; Larsen and Thorarinsson 1977).

Few studies of the long- and short-term effects of tephra fall on vegetation and environment have been made and understanding of environmental processes following tephra fall is largely lacking. However, changes in land use (Edwards et al. 2004), draining of wetland (Buckland et al. 1986; Edwards and Craigie 1998; Erlendsson et al. 2009) and degradation of vegetation (Ólafsdóttir and Guðmundsson 2002) have been recorded following tephra depositions during the Holocene. This paper presents palaeoenvironmental reconstructions before and after the deposition of the Hekla 4 tephra from two lakes in Northwest Iceland (Fig. 2). The reconstructions provide an insight into the responses of two relatively stable terrestrial ecosystems (Eddudóttir et al. 2015, 2016) to thick tephra deposits prior to large scale soil erosion and aeolian processes that have dominated the Icelandic environment after human settlement.

Study sites

Kagaðarhóll

Kagaðarhóll (Fig. 2; 65°35′16′′N, 20°07′58′′W, 114 m a.s.l.), is situated ~10 km southeast of Húnaflói bay. The site is a palaeolake about 4.5 ha in area that supports a bog vegetation community (Icelandic: *mýrar*) dominated by sedges (Cyperaceae spp.). *Eriophorum angustifolium* is the most abundant species, along with dwarf shrubs *Betula nana*, *Salix phylicifolia* and *Salix lanata* and the herb *Cardamine nymanii*. The bog is surrounded by *Betula nana* dominated dwarf-shrub heath, eroded gravelly hills and semi-improved grassland. The Hekla 4 tephra is about 8 cm thick in peat profiles in the area (Fig. 1b). Weather observations are available from a weather station in Blönduós about 10 km NW of Kagaðarhóll (Fig. 2; Table 1).

Table 1. Meteorological information from weather stations close to the study sites.

	Kagaðarhóll	**Barðalækjartjörn**
Closest weather station	Blönduós	Kolka
Period	1982-2013	1994 - 2014
Elevation	8 m.a.s.l.	505 m.a.s.l.
Mean tritherm temperature	~9.3°C	~7.8 °C
Mean July temperature	~9.9°C	~8.8 °C
Mean January temperature	~-1.4°C	~-4.4°C**
Mean annual precipitation	~456 mm*	~398 mm per year***

Unpublished data from the Icelandic Met Office.
*Mean rainfall 1982-2003.
**Data missing for 1994, 1996 and 2010.
***Data missing for 2003, 2004 ,2008, 2010 and 2011.

Barðalækjartjörn

Barðalækjartjörn (Fig. 2; 65°25,212' N, 19°52,388' W, 413 m a.s.l.), is located on the margins of Auðkúluheiði, a heath on the northern fringe of the central highlands, about 20 km south-southeast of Kagaðarhóll. The lake is about 10 ha in area and the lake margin is comprised of *Carex* dominated wetland. The surrounding slopes are either dominated by exposed, barren, gravels or hummocky dwarf shrub heath of *Betula nana, Calluna vulgaris* and *Salix* spp. The Hekla 4 tephra is about 7 cm thick in soil cores retrieved from wetlands in the area (Fig. 1c).There is no surface inflow to the lake; a single outlet at its northern end cuts its way through a series of wetlands. The closest weather station is at Kolka, located at the northern end of the Blöndulón reservoir (Fig. 2; Table 1), about 20 km south of Barðalækjartjörn.

Methods

Field methods and stratigraphy

The cores were retrieved from wetland covering the Kagaðarhóll palaeolake and through ice at Barðalækjartjörn, using a Livingstone piston corer with a Bolivia adaptor fitted with 75 mm diameter polycarbonate tubes. Magnetic susceptibility (MS) was measured with a Bartington MS2 meter and Bartington MS2F probe at contiguous 1 cm intervals on split core segments (Dearing 1994). Dry bulk density (DBD; g cm^{-3}) and organic matter (OM, measured by loss on ignition) were measured at 1 cm contiguous intervals. OM was measured by combusting 1.2 cm^3 of sediment at 550 °C for 5 hours (Bengtsson and Enell 1986). DBD was calculated by dividing the dry weight of a sample by the volume of the undisturbed sample (Brady and Weil 1996).

Pollen and plant macrofossil analysis

Contiguous 2 cm^3 subsamples for pollen analysis were collected at 1 cm intervals from the Kagaðarhóll core and 0.5 cm intervals from the Barðalækjartjörn core. A smaller sample interval was used for the Barðalækjartjörn core due to relatively low sediment accumulation rate in the core compared to the Kagaðarhóll core. Samples were prepared using standard chemical methods of 10% HCl, 10% NaOH and acetolysis (Faegri et al. 1989; Moore et al. 1991) and heavy-liquid separation (Björck et al. 1978; Nakagawa et al. 1998) using LST Fastfloat (a sodium heteropolytungstate solution; density 1.9 g cm^{-3}). A tablet containing spores of *Lycopodium clavatum* (batch no. 177745) was added to each sample (Stockmarr 1971) for calculations of pollen accumulation rates (PAR; grains cm^{-2} yr^{-1}). A minimum of 300 indigenous terrestrial pollen grains were counted for each sample, this count constituted the total land pollen (TLP) sum. Identification of pollen grains and spores was based on Moore et al. (1991) and a pollen type slide collection at the University of Iceland. Pollen and spore taxonomy followed Bennett (2016) and Erlendsson (2007).

Pollen categories and calculations followed Hallsdóttir (1987) and Caseldine et al. (2006). *Betula* pollen diameters were measured at 1000x magnification and non-triporate *Betula* pollen grains were recorded (Karlsdóttir et al. 2008). Pollen and macrofossil diagrams were constructed using TILIA (version 1.7.16) and pollen assemblage zones (PAZs), based on terrestrial pollen assemblages, were calculated in TILIA (Grimm 2011) using the CONISS program to aid zone placement.

Contiguous 5 cm thick plant macrofossil samples were analysed 10 cm either side of the tephra layer in the Kagaðarhóll core. For the Barðalækjartjörn core samples were analysed 5 cm above and below the tephra. Samples were washed through a 125 µm sieve and vascular plant remains were picked out for identification. Identification was based on references (e.g. Katz et al. 1965; Berggren 1969; Birks 2007; Cappers et al. 2012) and comparisons with reference material when available. Plant taxonomy follows Kristinsson (2010).

Principal component analysis

Detrended correspondence analysis (DCA) was initially performed on the terrestrial pollen data sets for both sites. First-axis gradient lengths of 0.34104 for the Kagaðarhóll data set and 0.54782 for the Barðalækjartjörn data set suggest linear responses in both data sets. Therefore Principal Component Analysis (PCA) was performed. The PCA analysis was performed on Hellinger transformed data consisting of terrestrial pollen taxa with percentages >1 %. Ordination was performed in R using the package vegan (Oksanen et al. 2016).

Core chronology

Linear age-depth models for both cores (Fig. 3) were constructed based on a series of tephra layers. The tephra layers used were; Hekla 3 (3000 cal B.P.; Dugmore et al. 1995), Hekla 4 (4200 cal B.P.; Dugmore et al. 1995) and HUN (5530 cal B.P.; see Eddudóttir et al. 2016 for dating and chemical composition of the tephra). Models were constructed using the R package Clam (Blaauw 2010). Ages are given in calibrated years before present (cal B.P.; with present assigned to A.D. 1950).

Results

Kagaðarhóll

The Kagaðarhóll record covers the period from *c*. 4400 to 4000 cal B.P. *Betula* pollen percentages are relatively high (~60-75 % of TLP) beneath the Hekla 4 tephra (PAZ 1; spanning ~200 years before the eruption) but increase temporarily above the tephra to ~83 % of TLP in PAZ 2 (Fig. 4). The percentage increase is not reflected in the *Betula* PAR which is stable at ~800-900 grains cm^{-2} yr^{-1} in PAZ 1 and 2 (Fig. 5). Mean *Betula* pollen diameters are ~22 µm below and above the tephra (Figs. 6a). Other pollen taxa have low relative abundances in PAZ 1, shrubs and dwarf shrubs of *Salix* and *Juniperus communis* range between ~2 and 4 % while *Empetrum nigrum* and *Vaccinium*-type are sporadically present. *Sorbus aucuparia* and *Thalictrum alpinum* pollen range between 0 and 1.5 % of TLP. Herb pollen such as *Angelica sylvestris*, *Caltha palustris*, *Oxyria digyna*, *Potentilla*-type and *Rumex acetosa* are recorded in low numbers (<1 %). Most pollen taxa decrease or disappear temporarily from the record above the tephra, most notably herb pollen, as well as *Juniperus communis* and *Sorbus aucuparia* pollen. The only herb pollen recorded immediately above the tephra belongs to *Oxyria digyna* and *Thalictrum alpinum*. *Caltha palustris* pollen also appear above the tephra (Fig. 4). Percentages of non-triporate *Betula* pollen range between ~3 and 11 % both below and above the tephra (Fig. 5). Pollen taxa that disappear above the tephra reappear after *c*. 4150 cal B.P. and the relative abundance of *Betula* decreases again to <80 % (Fig. 4). Few vascular plant macrofossils were found in the sediment (Table 2). Below the Hekla 4 tephra, *Betula pubescens* fruits and *Myriophyllum alterniflorum* seeds are recorded and *Betula pubescens* and *Betula nana* macrofossils are recorded above the tephra. Notably, the MS values are lower and more stable following the deposition of the tephra than before, the DBD ranges between ~0.13-0.24 g cm^{-3} below and ~0.14-0.21 g cm^{-3} above the tephra and OM values are higher (~23-34 %) above the tephra than below (~14-32 %) (Fig. 5).

Principal component analysis

The first axis explains 30.5 % of the variance in the dataset while the second axis explains 18.5 % (Fig. 7a). Initially the variance is explained by Poaceae, *Vaccinum*-type and *Rumex acetosa*. At *c*. 4300 cal B.P. there is a shift towards increased *Sorbus aucuparia*. The two samples immediately above the tephra plot together to the left along the first axis, mainly due to an increase in *Betula* pollen and a decrease and disappearance of other pollen types, such as *Sorbus aucuparia* and *Juniperus communis*. As more pollen types are recorded after *c*. 4150 cal B.P. and until *c*. 4000 cal B.P., pollen from *Empetrum nigrum*, along with Cyperaceae and *Ranunculus acris*-type become important.

Table 2. Plant macrofossils recorded in the Kagaðarhóll core. Counts are in parenthesis.

Pre-Hekla 4	**Post-Hekla 4**
Trees and shrubs:	**Trees and shrubs**
Betula pubescens fruit (3)	*Betula pubescens* fruit (4)
Aquatics:	*Betula nana* female catkin scale (1)
Myriophyllum alterniflorum seed (7)	*Betula nana* fruit (1)
Ranunculus confervoides fruit (1)	*Betula* undiff. fruit (1)
	Herbs:
	Carex undiff. fruit (1)
	Aquatics:
	Myriophyllum alterniflorum seed (2)

Barðalækjartjörn

The Barðalækjartjörn record covers the period from *c*. 4400 to 3600 cal B.P. Significant changes occur in the pollen assemblage following the deposition of the Hekla 4 tephra. The *Betula* pollen percentages decrease from ~33-47 % of TLP in PAZ 1 to values of ~30 % above the tephra (PAZ 2), while there is a relative increase in Cyperaceae pollen from ~25-33 % of TLP in PAZ 1 to >40 % in PAZ 2 (Fig. 8). *Salix* pollen decrease slightly above the tephra, from ~6-15 % of TLP to ~5-9 %, but *Juniperus communis* and *Vaccinium*-type pollen range from ~1-3 % of TLP in both PAZs. *Empetrum nigrum* percentages increase from ~0.3-0.7 % of TLP in PAZ 1 to ~0.7-1.7 % after *c*. 4000 cal B.P. *Thalictrum alpinum* pollen is the most common herb taxon (~1-4 %), while other herb taxa, such as *Angelica sylvestris*, Lactuceae, *Oxyria digyna*, *Potentilla*-type, *Ranunuculus acris*-type and *Rumex acetosa* are recorded in small numbers (Fig. 8). PARs are extremely low in both PAZ 1 and 2 (Fig. 9). The *Betula* PAR decreases above the tephra from ~49-73 in PAZ 1 to ~15-40 grains cm^{-2} yr^{-1} in PAZ 2. Mean *Betula* pollen diameters are ~21 μm in both PAZs, however more pollen grains with smaller diameters are recorded above the tephra (Fig. 6b). Percentages of non-triporate *Betula* pollen are high in all samples, ~4-13 % below the tephra and ~6-16 % above. Few vascular plant macrofossils are recorded; a *Betula nana* leaf and a female catkin scale are recorded above the tephra (Table 3). Magnetic susceptibility is low prior to tephra deposition and increases slightly above it. A similar trend is seen in the DBD with values of ~0.15-0.17 g cm^{-3} below and ~0.2-0.28 g cm^{-3} above the tephra. OM decreases from ~40% below the tephra to ~21-32 % above (Fig.9).

Table 3. Plant macrofossils recorded in the Barðalækjartjörn core. Counts are in parenthesis.

Pre-Hekla 4	**Post-Hekla 4**
Trees and shrubs:	**Trees and shrubs:**
Betula pubescens fruit (1)	*Betula nana* leaf (1)
Betula undiff. fruit (1)	*Betula nana* female catkin scale (1)
Aquatics:	*Salix* budscale (1)
Myriophyllum alterniflorum seed (11)	**Herbs:**
Ranunculus confervoides fruit (1)	*Carex* fruit (2)
Pteridophytes	**Aquatics:**
Selaginella selaginoides megaspore (1)	*Myriophyllum alterniflorum* seed (1)
	Pteridophytes
	Selaginella selaginoides megaspore (5)

Principal component analysis

The first axis explains 32.4 % of the variability in the data set and the second axis 16.6 % (Fig. 7b). Below the tephra herbs, dwarf shrubs and trees are important components of the assemblage, including *Sorbus aucuparia* and *Salix* for the earliest samples and the herbs *Rumex acetosa* and *Oxyria digyna* immediately before the tephra was deposited. Above the tephra there is a shift towards the dwarf shrubs *Vaccinium*-type and *Empetrum nigrum*, as well as Cyperaceae.

Discussion

Kagaðarhóll

For the *c*. 200 years before the Hekla 4 eruption (PAZ 1) lake Kagaðaðarhóll was surrounded by open *Betula pubescens* woodland. Mean *Betula* pollen grain diameter of ~22 µm (Fig. 6a) suggest that *Betula pubescens* produced most of the *Betula* pollen deposited in the lake (Mäkelä 1996). Relatively high *Betula* pollen percentages of ~60-75% of TLP (Fig. 4) and a *Betula* PAR of >600 grains cm^{-2} yr^{-1} (Fig. 5), probably represent a relatively open woodland (Hicks 2001; Eddudóttir et al. 2015). *Juniperus communis* pollen is present at low percentages, but may have been an important component of the vegetation community, as the pollen is not well represented in pollen assemblages (Birks 1973). The presence of *Juniperus communis* indicates a relatively open canopy (Thomas et al. 2007). Additional indication of a relatively open canopy is the presence of *Sorbus aucuparia* (rowan) pollen in the record as pollen from rowan trees are underrepresented in pollen records from dense woodlands (Birks 1973; Hallsdóttir 1995). The abundance of pollen representing understory vegetation is relatively low, mainly due to the high concentrations of *Betula* pollen. However, the pollen of *Salix* and *Vaccinium*-type and of herbs *Angelica sylvestris, Oxyria digyna*, *Potentilla*-type, *Rumex acetosa, Ranunculus acris*-type and *Thalictrum alpinum* is present in low abundances (Fig. 4).

Changes are recorded in the pollen assemblage after the Hekla 4 eruption (PAZ 2). The most significant change is the temporary disappearance of herbs apart from *Thalictrum alpinum* and *Oxyria digyna* for at least 50 years (Fig. 4). The pollen assemblage during this period is markedly different from the rest of the record due to a relative increase in *Betula* pollen and the disappearance of several herb taxa (Fig. 4, 7a). The loss of herbs may indicate that taxa growing in the understory of the woodland were buried by the thick tephra deposit. Thick tephra deposits can prevent regrowth of herbs that are not able to grow up through the tephra. *Vaccinium*-type pollen disappear temporarily following the deposition of the Hekla 4 tephra (Figs. 4, 5), which may indicate burial as the dwarf shrub *Vaccinium uliginosum* is intolerant of burial by aeolian material (Vilmundardóttir et al. 2009). Tephra layers can create a crust which buried plants cannot penetrate (Mack 1987) and thick layers can lead to low nitrogen and phosphorus availability for plants (Zobel and Antos 1997). The Hekla 4 tephra is about 8 cm thick in soil profiles from the region near lake Kagaðarhóll (Fig. 1b). Considering that compaction can reduce the thickness of tephra layers by up to half of fresh deposits (Sarna-Wojcicki et al. 1981), the maximum thickness of freshly deposited material around Kagaðarhóll may have been as much as 16 cm. In comparison, during the 1980 eruption of Mount St. Helens, virtually all herbaceous plants were destroyed where tephra deposits were 12-15 cm in thickness (Antos and Zobel 2005; Zobel and Antos 2007). Under such conditions a new substratum is created by the tephra and opportunities arise for pioneer plants to colonise the new surface, changing the species composition (Antos and Zobel 2005). This may explain the increased presence of pollen of hardy pioneer *Empetrum nigrum* (Kristinsson 2010) following the eruption (Fig. 4, 5).

The tephra fall probably did not have long-term adverse effects on birch trees at Kagaðarhóll. An increase in the relative abundance of *Betula* pollen is recorded following the eruption from ~60-75 % of TLP to ~83 % (Fig. 4). This increase is probably due to a decrease in the deposition of other pollen types, as the *Betula* PAR remains unchanged at ~800-900 grains cm^{-2} yr^{-1} before and after the eruption (Fig. 5). Mean *Betula* pollen diameters of ~22 μm both before and after the eruption suggest that the characteristics of the birch population were not affected by the tephra fall (Fig. 6a). Little change in the percentage of non-triporate *Betula* after the eruption also indicates that hybridisation between *Betula pubescens* and *Betula nana* did not increase following the eruption (Fig. 5), although *Betula nana* macrofossils are recorded after the eruption, and not before (Table 2). This suggests that the tephra fall did not have a significant impact on the *Betula pubescens* population.

The vegetation assemblage begins to recover after a minimum period of about 50 years. The composition of the pollen assemblage of the woodland community is similar to that from before the eruption, albeit with a decrease in some taxa such as *Juniperus communis* and *Thalictrum alpinum* (Figs. 4, 5). *Juniperus communis* is a shade intolerant species (Thomas et al. 2007) and this decrease may indicate that the canopy was more closed than before the eruption. The change in assemblage and increase in pollen taxa recorded probably represents the recovery of the understory. When tephra deposits are relatively thick recovery can take a long time, e.g. vegetation had not recovered to its former composition, or cover, 20 years after the eruption of Mount St. Helens in areas where the tephra layer was only 4.5 cm thick (Antos and Zobel 2005).

The relatively stable woodland at Kagaðarhóll was able to recover relatively quickly to a state similar to that before the eruption (Fig. 7a), despite burial of vegetation in the understory and a period of plant recolonisation. The tephra could settle in the tall vegetation of the woodland around lake Kagaðarhóll which probably trapped large volumes of the tephra and prevented reworking by wind (Cutler et al. 2016). The stability of the environment after the eruption is reflected in little changes in MS, DBD and OM before and after the tephra was deposited (Fig. 5). This highlights the resilience of woodlands to tephra fall, and the protective capabilities of woodland to remobilisation of tephra and its removal into the lake.

Barðalækjartjörn

For the *c*. 200 years before the Hekla 4 eruption (PAZ 1) Barðalækjartjörn was probably surrounded by open *Betula pubescens* woodland and situated close to the altitudinal limit of the species. The mean *Betula* pollen diameter of ~21 µm (Fig. 6b) is smaller than at lake Kagaðarhóll. However, the absence of *Betula nana* macrofossils from the sediment (Table 3) indicates that *Betula* pollen was probably produced mainly by *Betula pubescens* (Eddudóttir et al. 2016). Relatively low *Betula* pollen percentages between 33 and 47 % of TLP (Fig. 8) and extremely low *Betula* PAR of ~49-73 grains cm^{-2} yr^{-1} (Fig. 9) may suggest that *Betula pubescens* plants were under stress, causing low pollen production (Kuoppamaa et al. 2009; Birks and Bjune 2010; Eddudóttir et al. 2016). The presence of *Salix* (~6-15 % of TLP) and *Juniperus communis* (~1-3 % of TLP), shows that these shrubs probably grew locally alongside *Betula pubescens*. Plants in the understory are represented by pollen from dwarf shrubs of *Vaccinium*-type and herbs such as *Galium*, *Potentilla*-type, *Ranunculus acris*-type and *Thalicrum alpinum*. Relatively high percentages (~25-33 % of TLP) of Cyperaceae probably reflect wetlands around the lake (Figs. 8, 9).

The Hekla 4 tephra represents a major boundary between vegetation communities in the Barðalækjartjörn record, marked by a significant change in the pollen assemblage after the eruption (PAZ 2; Fig. 7b). The most noticeable change above the tephra is the decrease in *Betula* pollen percentages from 34-47 % to ~30 % of TLP (Fig. 8) and PAR below 40 grains cm^{-2} yr^{-1} (Fig. 9). This is accompanied by a larger range of *Betula* pollen diameters and a relative increase in pollen grains with diameters of 17 and 18 µm (Fig. 6b), characteristic of *Betula nana* (Mäkelä 1996). The increase in *Betula nana* pollen is supported by the first appearance of *Betula nana* macrofossils for the latter half of the

Holocene (Table 3) (Eddudóttir et al. 2016). The increase in *Betula nana* shows that conditions became more difficult for *Betula pubescens* and the species was probably better able to survive at lower elevations. Pollen deriving from *Vaccinium*-type increase after *c*. 4200 cal B.P. and from *Empetrum nigrum* from *c*. 4000 cal B.P. (Figs. 8, 9), suggesting a change from open birch woodland to dwarf shrub heath. Cyperaceae increases from 25-33 % of TLP to >40 % after the eruption (Fig. 8). However, it is difficult to interpret the increase in Cyperaceae pollen due to the large ecological range of species within the family. It is not possible to determine if burial by the tephra affected herbs and other low growing plants in a similar manner to that at Kagaðarhóll as the temporal resolution in deposits overlying the Hekla 4 tephra is relatively low (74 years per pollen sample; Fig. 3) due to low sediment accumulation between the Hekla 3 and 4 tephra layers.

The Barðalækjartjörn record ends *c*. 3600 cal B.P., and shows clearly that during the *c*. 600 years following the eruption the floristic environment did not recover to the condition it was in immediately prior to the deposition of the Hekla 4 tephra (Fig. 7b). The tephra fell at a time period that has been identified as trending towards irreversible cooling climate in several lake records from *c*. 4200 cal B.P. (Larsen et al. 2012; Geirsdóttir et al. 2013; Blair et al. 2015). A combination of cooling climate and the effects of the tephra fall may have caused the changes. Cold climate can affect recovery of ecosystems and even prevent recovery to a previous state (Arnalds 2013a). At Barðalækjartjörn an ecosystem already under stress due to cooling climate gave way to more resilient dwarf shrub heath after the tephra fell. This is in accordance with previous pollen studies that have shown that long term or even permanent changes in vegetation communities can result from tephra fall (Edwards and Craigie 1998; Edwards et al. 2004; Erlendsson et al. 2009).

Vegetation cover and stability

Vegetation cover and vegetation structure are crucial factors in stabilising tephra deposits and the capacity of vegetation to trap tephra increases with vegetation height (Arnalds 2013b; Cutler et al. 2016). At the time of the Hekla 4 eruption, woodlands and mires probably covered most of the Icelandic lowlands (Hallsdóttir 1995; Hallsdóttir and Caseldine 2005; Eddudóttir et al. 2015) while open woodland, dwarf shrub heath and wetlands dominated at higher altitudes (Wastl et al. 2001; Eddudóttir et al. 2016). These relatively stable environments would have been able to entrap a large proportion (Arnalds 2015; Cutler et al. 2016) of the ~6 km^3 of tephra that fell on land during the eruption (Larsen and Thorarinsson 1977). In contrast, deserts now cover about ~42 % of the country and only about 1.2 % of Iceland is covered by natural birch woodlands (Gísladóttir et al. 2014). When tephra is deposited on unvegetated or scarcely vegetated surfaces it is readily eroded and redistributed (Arnalds et al. 2013; Cutler et al. 2016). In such environments deposits of only a few centimetres thickness can have a negative environmental impact (Arnalds et al. 2013). The infamous Eyjafjallajökull eruption of 2010 was relatively small, only producing a volume of ~0.27 km^3 of airborne tephra (Gudmundsson et al. 2012). However, during the summer that followed tephra deposited on barren and sparsely vegetated surfaces was redistributed by wind and moved hundreds of kilometres from where it had originally lain (Arnalds et al. 2013). Resuspension of tephra also caused high concentrations of particulate matter in the air in South and Southwest Iceland during the summer following the Eyjafjallajökull eruption (Thorsteinsson et al. 2012). Repeated dust storms affecting air quality are already common in Iceland (Thorsteinsson et al. 2011, 2012; Arnalds et al. 2016) and it is clear that the current environment would not be capable of containing deposits of the same magnitude and distribution as the Hekla 4 tephra. Such a large and widespread tephra fall, covering most of the country, would probably lead to an extended period of increased dust storms and poor air quality. This highlights the importance of re-establishing vegetation cover in Iceland in order to prepare for large eruptions and minimise their damaging potential. Greater vegetation cover, especially tall vegetation, would better stabilise tephra deposits and hinder tephra redistribution (Cutler et al. 2016), potentially mitigating the effects of large-scale tephra fall. As this study shows, native birch woodland and dwarf shrub heath communities are well adapted to such circumstances, depending upon their context according to altitude and climate.

Conclusions

The Kagaðarhóll and Barðalækjartjörn records demonstrate the effects of tephra on two different ecosystems during a period of cooling climate. The stable woodland at Kagaðarhóll was better adapted, despite the understory vegetation being buried by tephra, the woodland ecosystem recovered relatively quickly from the impact of the tephra deposition. In contrast, the open woodland at Barðalækjartjörn that was already at its ecological limit eventually shifted to a dwarf shrub heath, a more resilient vegetation community that was better suited to the new environmental conditions. These results emphasise the impact of tephra fall on pollen archives, and underscore the importance of vegetation cover in the event of heavy tephra fall. The low resilience of the current Icelandic environment in the event of tephra fall of the size of the Hekla 4 tephra is of concern. A similar event would have serious environmental consequences today, and could lead to poor air quality and health complications for an extended period following an eruption.

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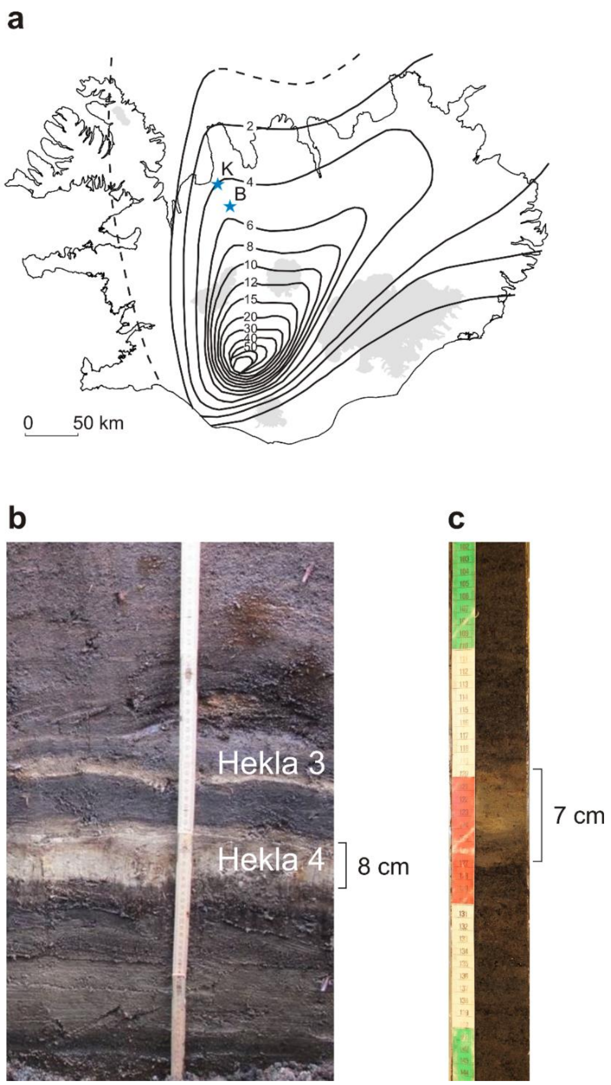

Fig. 1 Distribution and thickness of the Hekla 4 tephra layer. **a** Isopach map of the Hekla 4 tephra layer, with thickness in centimetres (Adapted from Larsen and Thorarinsson 1977). Stars denote study sites Kagaðarhóll (K) and Barðalækjartjörn (B). **b** Soil profile from a wetland close to Kagaðarhóll, including tephra layers Hekla 4 and Hekla 3 **c** The Hekla 4 tephra layer in a soil core from a wetland close to Barðalækjartjörn. The parenthesis indicate the thickness of the Hekla 4 tephra.

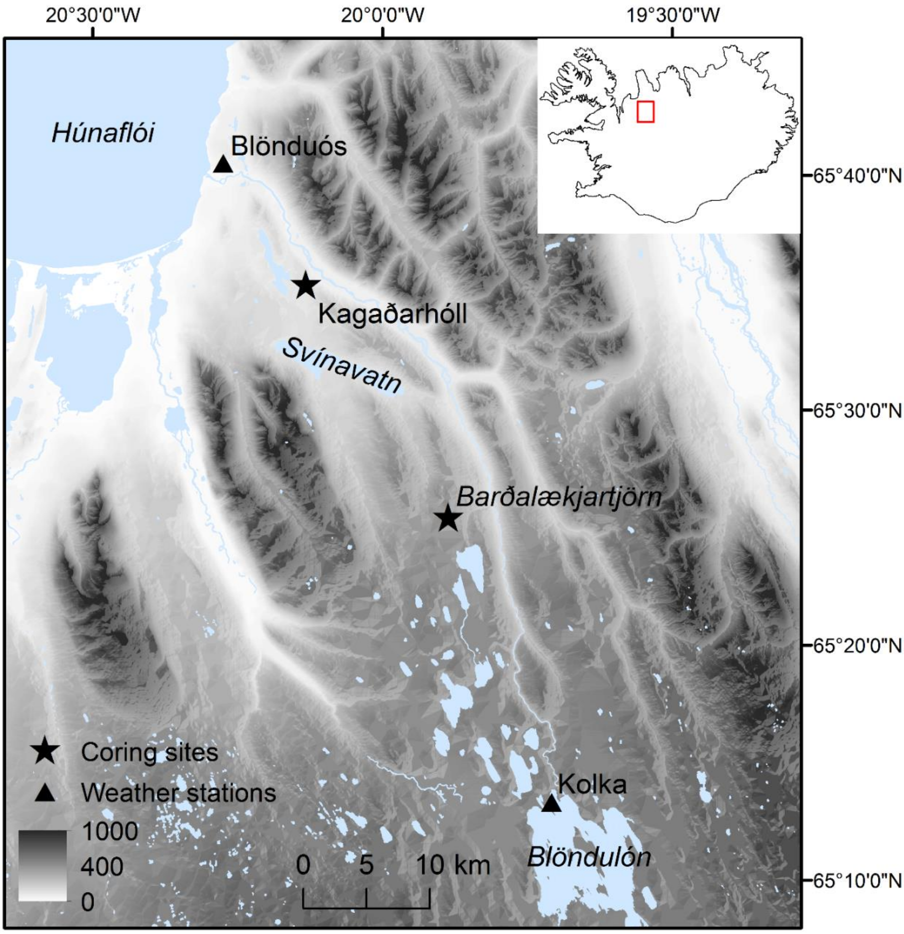

Fig. 2 Map showing the location of the study sites.

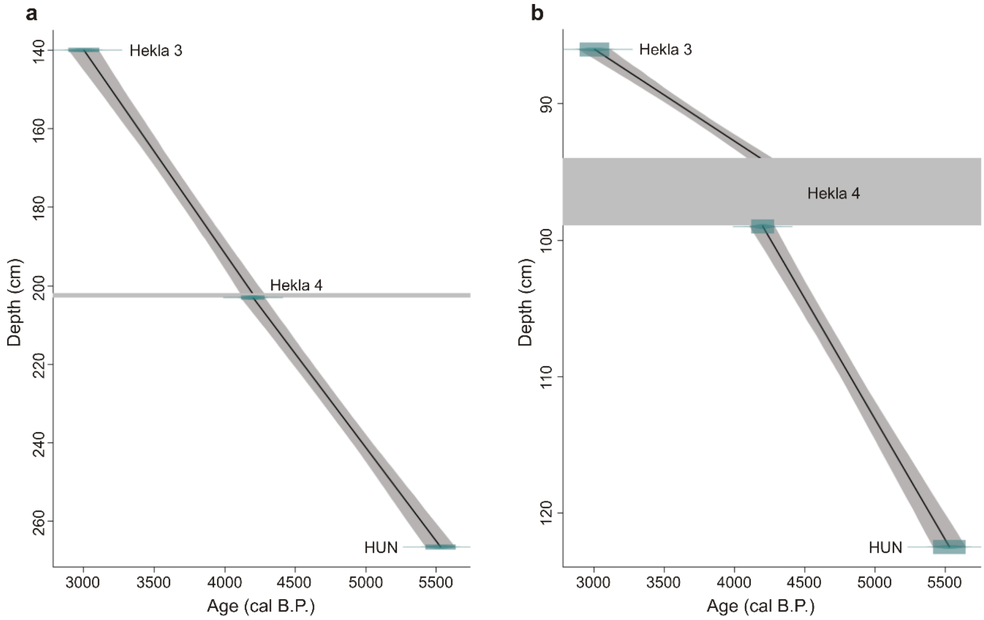

Fig. 3 Age-depth models for **a** Kagaðarhóll and **b** Barðalækjartjörn. Green symbols represent previously dated tephra layers. The black line shows the best-fit model and the grey area represents the 95% confidence interval. Horizontal grey lines show the Hekla 4 tephra layer.

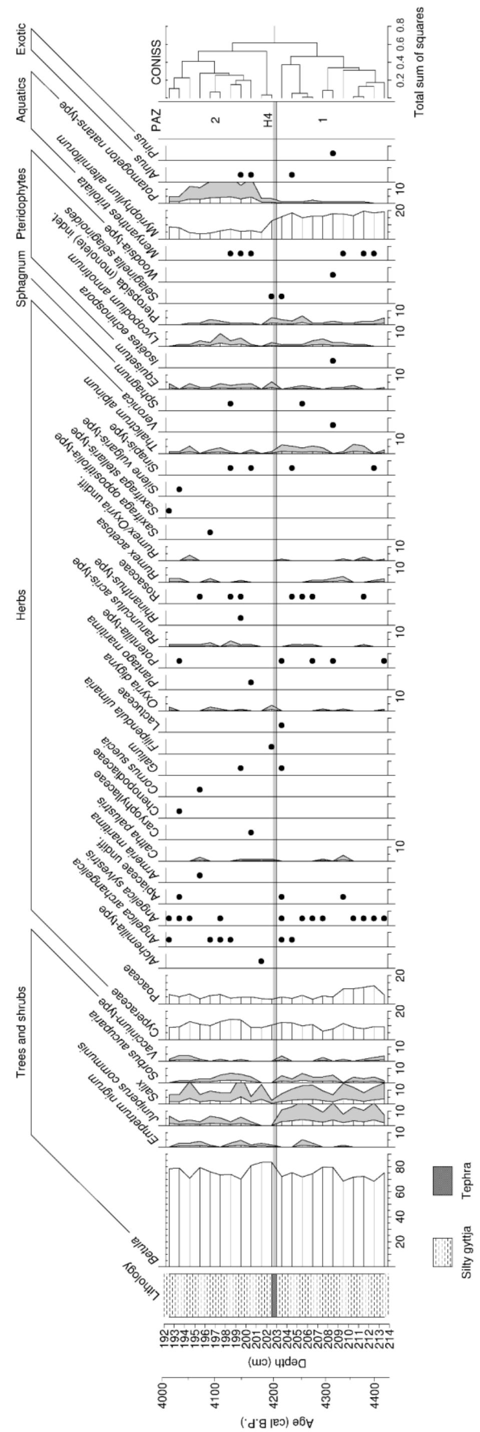

Fig. 4 Percentage pollen diagram for the Kagaðarhóll core; x4 exaggeration curves. Dots signify percentages <1%.

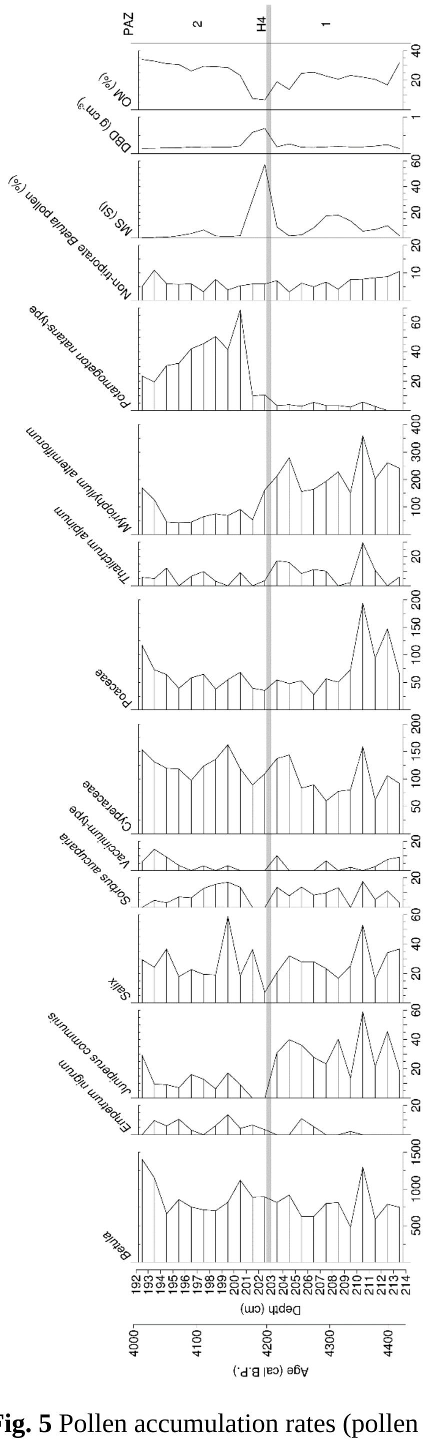

Fig. 5 Pollen accumulation rates (pollen grains cm^{-2} year^{-1}) of selected pollen taxa, non-triporate *Betula* pollen (%), magnetic susceptibility (MS), dry bulk density (DBD) and organic matter (OM) for the Kagaðarhóll core.

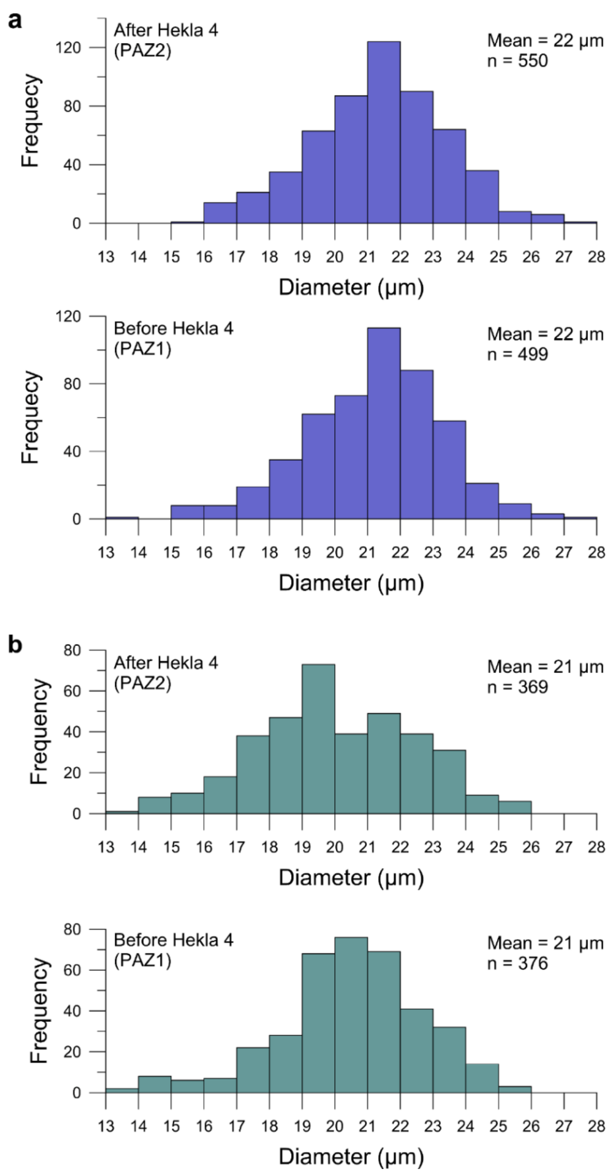

Fig. 6 Measured *Betula* pollen grains for the **a** Kagaðarhóll and **b** Barðalækjartjörn cores.

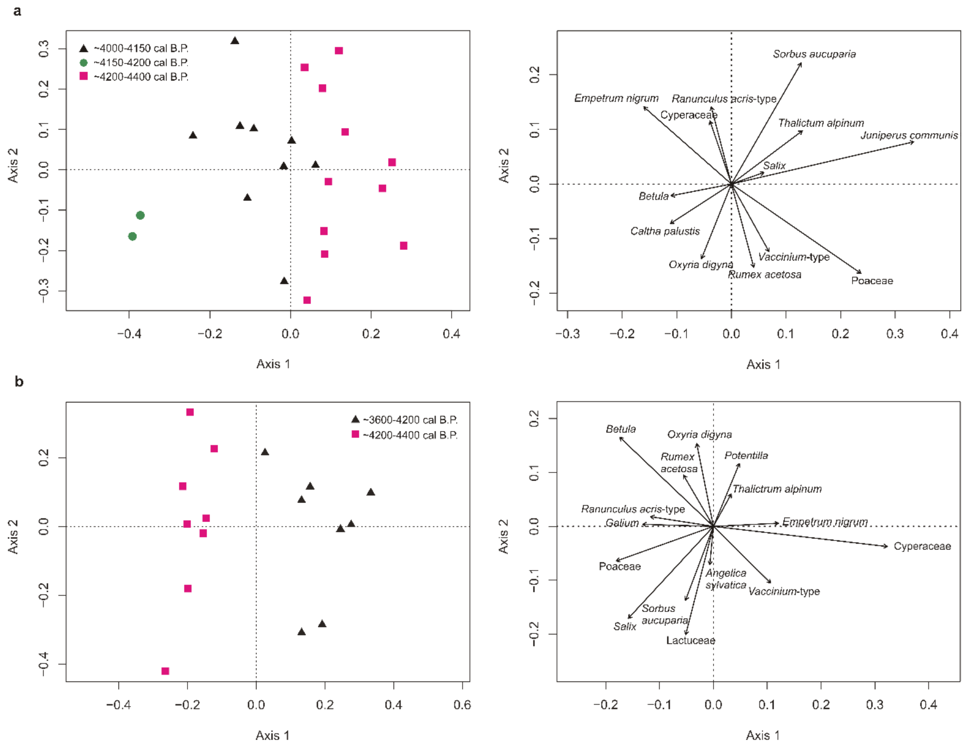

Fig. 7 Principal component analysis of terrestrial pollen assemblages from **a** Kagaðarhóll and **b** Barðalækjartjörn.

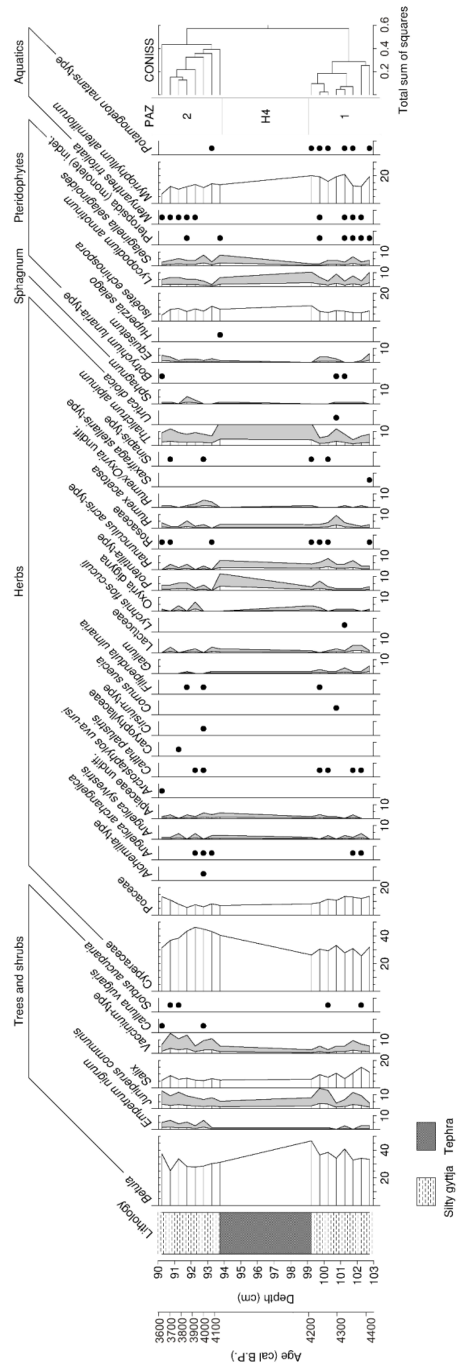

Fig. 8 Percentage pollen diagram for the Barðalækjartjörn core; x4 exaggeration curves. Dots signify percentages <1%.

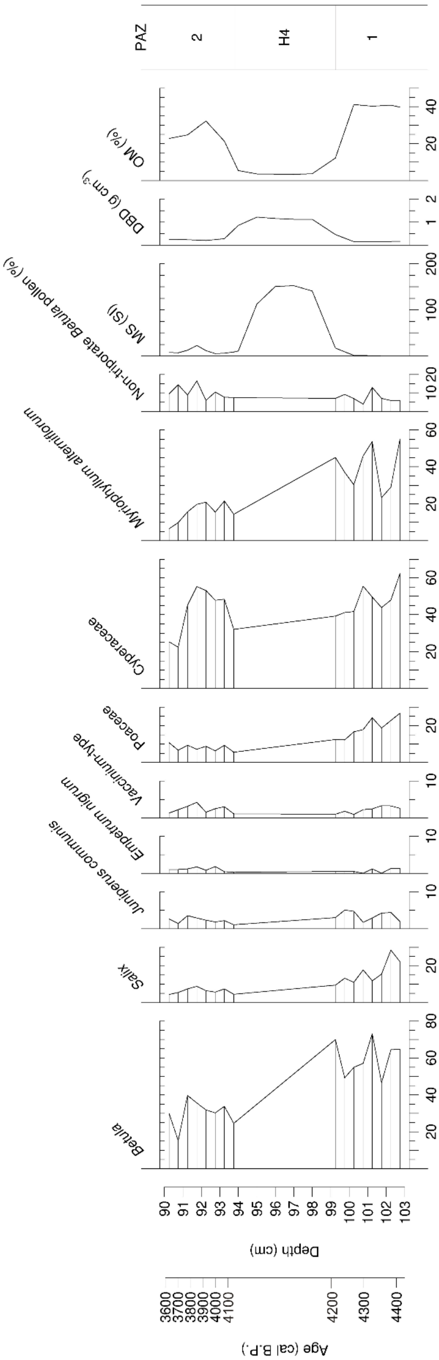

Fig. 9 Pollen accumulation rates (pollen grains cm^{-2} $year^{-1}$) of selected taxa, non-triporate *Betula* pollen (%), magnetic susceptibility (MS), dry bulk density (DBD) and organic matter (OM) for the Barðalækjartjörn core.

References

Antos JA, Zobel DB (2005) Plant responses in forests of the tephra-fall zone. In: Dale VH, Swanson FJ, Crisafulli, CM (eds) Ecological responses to the 1980 eruption of Mount St. Helens. Springer New York, pp 47-58

Arnalds O (2013a) The influence of volcanic tephra (ash) on ecosystems. Advances in Agronomy 121:332-380

Arnalds O (2013b) The influence of volcanic tephra (ash) on ecosystems. In: Sparks D (ed) Advances in Agronomy, vol 121. Elsevier, Amsterdam, pp 332-380

Arnalds O, Dagsson-Waldhauserova P, Olafsson H (2016) The Icelandic volcanic aeolian environment: Processes and impacts — A review. Aeolian Research 20:176-195. doi:http://dx.doi.org/10.1016/j.aeolia.2016.01.004

Arnalds O, Thorarinsdottir EF, Thorsson J, Waldhauserova PD, Agustsdottir AM (2013) An extreme wind erosion event of the fresh Eyjafjallajokull 2010 volcanic ash. Scientific reports 3:1257

Arnalds O (2015) The soils of Iceland. Springer, Dordrecht

Bengtsson L, Enell M (1986) Chemical analysis. In: Berglund BE (ed) Handbook of Holocene Palaeoecology and Palaeohydrology. John Wiley & Sons, Chichester, pp 423-451

Bennett KD (2016) Catalogue of pollen types. Queen's University of Belfast. http://www.chrono.qub.ac.uk/pollen/pc-intro.html. Accessed 30 April 2016.

Berggren G (1969) Atlas of seeds and small fruits of Northwestern-European plant species (Sweden, Norway, Denmark, East Fennoscandia and Iceland) with morphological descriptions: Part 2 Cyperaceae. Swedish Natural Science Research Council, Stockholm

Birks HH (2007) Plant Macrofossils - Introduction. In: Elias SA (ed) Encyclopedia of Quaternary Science, 2nd edn. Elsevier, pp 2266-2288

Birks HH, Bjune AE (2010) Can we detect a west Norwegian tree line from modern samples of plant remains and pollen? Results from the DOORMAT project. Vegetation History and Archaeobotany 19:325-340. doi:10.1007/s00334-010-0256-0

Birks HJB (1973) Modern pollen studies in some arctic and alpine environments. In: Birks HJB, West RG (eds) Quaternary Plant Ecology. Blackwell, Oxford, pp 143-168

Björck S, Persson T, Kristersson I (1978) Comparison of two concentration methods for pollen in minerogenic sediments. GFF 100:107-111

Blaauw M (2010) Methods and code for ‘classical’ age-modelling of radiocarbon sequences. Quaternary Geochronology 5:512-518. doi:http://dx.doi.org/10.1016/j.quageo.2010.01.002

Blair CL, Geirsdottir A, Miller GH (2015) A high-resolution multi-proxy lake record of Holocene environmental change in southern Iceland. Journal of Quaternary Science 30:281-292

Brady NC, Weil RR (1996) Elements of the Nature and Properties of Soils, 2nd edn. Pearson Prentice-Hall, Upper Saddle River

Buckland P, Gerrard A, Larsen G, Perry D, Savory D, Sveinbjarnardóttir G (1986) Late Holocene palaeoecology at Ketilsstadir in Mýrdalur, South Iceland. Jökull:41-55

Cappers RTJ, Bekker RM, Jans JEA (2012) Digitale Zadenatlas van Nederland, 2nd edn. Barkhuis & Groningen University Library, Groningen

Carey RJ, Houghton BF, Thordarson T (2010) Tephra dispersal and eruption dynamics of wet and dry phases of the 1875 eruption of Askja Volcano, Iceland. Bulletin of Volcanology 72:259-278. doi:10.1007/s00445-009-0317-3

Carlsen HK, Gislason T, Benediktsdottir B, Kolbeinsson TB, Hauksdottir A, Thorsteinsson T, Briem H (2012a) A survey of early health effects of the Eyjafjallajökull 2010 eruption in Iceland: a population-based study. BMJ open 2:e000343. doi:10.1136/bmjopen-2011-00034

Carlsen HK et al. (2012b) Health effects following the Eyjafjallajökull volcanic eruption: a cohort study. BMJ open 2:e001851. doi:10.1136/bmjopen-2012-001851

Caseldine C, Geirsdóttir Á, Langdon P (2003) Efstadalsvatn–a multi-proxy study of a Holocene lacustrine sequence from NW Iceland. Journal of Paleolimnology 30:55-73

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 25:2314-2331

Cutler NA, Bailey RM, Hickson KT, Streeter RT, Dugmore AJ (2016) Vegetation structure influences the retention of airfall tephra in a sub-Arctic landscape. Progress in Physical Geography 40:661-675. doi:10.1177/0309133316650618

Dearing J (1994) Environmental magnetic susceptibility Using the Bartington MS2 system. Chi Publishing, Kenilworth

Dugmore AJ et al. (2005) The Norse landnám on the North Atlantic islands: an environmental impact assessment. Polar Record 41:21-37

Dugmore AJ, Church MJ, Mairs K-A, McGovern TH, Perdikaris S, Vésteinsson O (2007) Abandoned farms, volcanic impacts, and woodland management: revisiting Þjórsárdalur, the "Pompeii of Iceland". Arctic Anthropology 44:1-11

Dugmore AJ, Cook GT, Shore JS, Newton AJ, Edwards KJ, Larsen G (1995) Radiocarbon dating tephra layers in Britain and Iceland. Radiocarbon 37:379-388

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

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. The Holocene 25:1437-1453

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

Edwards K, Craigie R (1998) Palynological and vegetational changes associated with the deposition of Saksunarvatn ash in the Faroe Islands. Fróðskaparrit 46:245-258

Edwards KJ, Dugmore AJ, Blackford JJ (2004b) Vegetational response to tephra deposition and land-use change in Iceland: a modern analogue and multiple working hypothesis approach to tephropalynology. Polar Record 40:113-120

Edwards KJ, Lawson IT, Erlendsson E, Dugmore AJ (2005) Landscapes of contrast in Viking age Iceland and the Faroe Islands. Landscapes 6:63-81

Einarsson P (2008) Plate boundaries, rifts and transforms in Iceland. Jökull 58:35-58

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

Erlendsson E, Edwards KJ, Buckland PC (2009) Vegetational response to human colonisation of the coastal and volcanic environments of Ketilsstaðir, southern Iceland. Quaternary Research 72:174-187

Faegri K, Kaland PE, Krzywinski K (1989) Textbook of Pollen Analysis. 4th edn. John Wiley & Sons, New York

Gathorne-Hardy FJ, Erlendsson E, Langdon PG, Edwards KJ (2009) Lake sediment evidence for late Holocene climate change and landscape erosion in western Iceland. Journal of Paleolimnology 42:413-426

Geirsdóttir Á, Miller GH, Larsen DJ, Ólafsdóttir S (2013) Abrupt Holocene climate transitions in the northern North Atlantic region recorded by synchronized lacustrine records in Iceland. Quaternary Science Reviews 70:48-62. doi:http://dx.doi.org/10.1016/j.quascirev.2013.03.010

Gísladóttir FÓ, Brink SH, Arnalds Ó (2014) Nytjaland (Icelandic Farmland Database). Agricultural University of Iceland Report 49. In Icelandic, English summary.

Gísladóttir G, Erlendsson E, Lal R (2011) Soil evidence for historical human-induced land degradation in West Iceland. Applied Geochemistry 26:S28-S31. doi:http://dx.doi.org/10.1016/j.apgeochem.2011.03.021

Grimm EC (2011) TILIA 1.7.16. Illinois state museum, Springfield

Gudmundsson MT et al. (2012) Ash generation and distribution from the April-May 2010 eruption of Eyjafjallajökull, Iceland. Scientific Reports 2:572. doi:10.1038/srep00572

Hallsdóttir M (1987) Pollen analytical studies of human influence on vegetation in relation to the landnám tephra layer in southwest Iceland. PhD Thesis, Lund University
Hallsdóttir M (1995) On the pre-settlement history of Icelandic vegetation. Búvísindi 9:19-29
Hallsdóttir M, Caseldine CJ (2005) The Holocene vegetation history of Iceland, state-of-the-art and future research. In: Caseldine C, Russel, A., Harðardóttir, J. and Knudsen, Ó. (ed) Iceland – modern processes and past environments. Elsevier, Amsterdam, pp 319-334
Hicks S (2001) The use of annual arboreal pollen deposition values for delimiting tree-lines in the landscape and exploring models of pollen dispersal. Review of Palaeobotany and Palynology 117:1-29. doi:http://dx.doi.org/10.1016/S0034-6667(01)00074-4
Horwell C, Baxter P, Kamanyire R (2015) Health impacts of volcanic eruptions. In: Loughlin SC, Sparks S, Brown SK, Jenkins SF and Vye-Brown C (eds) Global Volcanic Hazards and Risk. Cambridge University Press, Cambridge, pp 289-294
Horwell CJ, Baxter PJ (2006) The respiratory health hazards of volcanic ash: a review for volcanic risk mitigation. Bulletin of Volcanology 69:1-24. doi:10.1007/s00445-006-0052-y
Karlsdóttir L, Hallsdóttir M, Thórsson AT, Anamthawat-Jónsson K (2008) Characteristics of pollen from natural triploid Betula hybrids. Grana 47:52-59. doi:10.1080/00173130801927498
Katz NJ, Katz SV, Kipiani MG (1965) Atlas and keys of fruits and seeds occuring in the Quaternary deposits of the USSR. Publishing House Nauka, Moscow
Kristinsson H (2010) Flowering plants and ferns of Iceland. Mál og menning, 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 24:513-521
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. Quaternary Science Reviews 39:14-25
Larsen G, Gudmundsson MT, Vogfjörð K, Ilyinskaya E, Oddsson B, Pagneux E (2015a) The Bárðarbunga volcanic system. In: Ilyinskaya E, Larsen G and Gudmundsson M (eds.): Catalogue of Icelandic Volcanoes. IMO, UI, CPD-NCIP.
Larsen G, Gudmundsson MT, Vogfjörð K, Ilyinskaya E, Oddsson B, Pagneux E (2015b) The Katla volcanic system. In: Ilyinskaya E, Larsen G and Gudmundsson M (eds.): Catalogue of Icelandic Volcanoes. IMO, UI, CPD-NCIP.
Larsen G, Thorarinsson S (1977) H4 and other acid Hekla tephra layers. Jökull 27:28-46
Larsen G, Thordarson T, Vogfjörð K, Ilyinskaya E, Oddsson B, Pagneux E (2015c) The Hekla volcanic system. In: Ilyinskaya E, Larsen G and Gudmundsson M (eds.): Catalogue of Icelandic Volcanoes. IMO, UI, CPD-NCIP.
Liu E, Cashman K, Beckett F, Witham C, Leadbetter S, Hort M, Guðmundsson S (2014) Ash mists and brown snow: Remobilization of volcanic ash from recent Icelandic eruptions. Journal of Geophysical Research: Atmospheres 119:9463-9480
Mack RN (1987) Effects of Mount St Helens ashfall in steppe communities of eastern Washington: one year later. In: Bilderback DE (ed) Mount St Helens 1980 – Botanical Consequences of the Explosive Eruptions. University of California Press, Berkeley, pp 262-281
Mäkelä EM (1996) Size distinctions between Betula pollen types—a review. Grana 35:248-256
McGovern TH et al. (2007) Landscapes of settlement in northern Iceland: Historical ecology of human impact and climate fluctuation on the millennial scale. American Anthropologist 109:27-51
Moore PD, Webb JA, Collison ME (1991) Pollen analysis. Blackwell scientific publications, Oxford
Nakagawa T, Brugiapaglia E, Digerfeldt G, Reille M, Beaulieu J-LD, 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. doi:10.1111/j.1502-3885.1998.tb00864.x
Oksanen J et al. (2016) vegan: Community Ecology Package, R package version 2.3-3 edn.,

Ólafsdóttir R, Guðmundsson HJ (2002) Holocene land degradation and climatic change in northeastern Iceland. The Holocene 12:159-167

Sarna-Wojcicki A, Shipley S, Waitt R, Dzuricin D, Wood S (1981) Areal distribution, thickness, mass, volume and grain size of air-fall ash from the six major eruptions of 1980. In: Lipman PW, Mullineaux DR (eds) The 1980 eruption of Mount St. Helens. Washington Govt Printing Office, Washington DC,

Sharma K, Self S, Blake S, Thordarson T, Larsen G (2008) The AD 1362 Öræfajökull eruption, SE Iceland: Physical volcanology and volatile release. Journal of Volcanology and Geothermal Research 178:719-739

Sigmundsson F, Pinel V, Lund B, Albino F, Pagli C, Geirsson H, Sturkell E (2010) Climate effects on volcanism: influence on magmatic systems of loading and unloading from ice mass variations, with examples from Iceland. Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences 368:2519-2534

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

Thomas PA, El-Barghathi M, Polwart A (2007) Biological Flora of the British Isles: Juniperus communis L. Journal of Ecology 95:1404-1440. doi:10.1111/j.1365-2745.2007.01308.x

Thorarinsson S (1944) Tefrokronologiska studier på Island. Pjórsárdalur och Dess Förödelse. Geografiska annaler 26:1-217

Thorarinsson S (1958) The Öræfajökull eruption of 1362. Acta Naturalia Islandica II:101

Thordarson T, Höskuldsson Á (2008) Postglacial volcanism in Iceland. Jökull 58:197-228

Thorsteinsson T, Gísladóttir G, Bullard J, McTainsh G (2011) Dust storm contributions to airborne particulate matter in Reykjavík, Iceland. Atmospheric Environment 45:5924-5933. doi:http://dx.doi.org/10.1016/j.atmosenv.2011.05.023

Thorsteinsson T, Jóhannsson T, Stohl A, Kristiansen NI (2012) High levels of particulate matter in Iceland due to direct ash emissions by the Eyjafjallajökull eruption and resuspension of deposited ash. Journal of Geophysical Research: Solid Earth 117

Thorvaldsdóttir S, Sigbjörnsson R (2015) Framing the 2010 Eyjafjallajökull volcanic eruption from a farming-disaster perspective. Natural Hazards 77:1619-1653

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. The Holocene 21:979-995. doi:10.1177/0959683611400201

Vilmundardóttir OK, Magnússon B, Gísladóttir G, Magnússon SM (2009) Gróðurframvinda í áfoksgeira í mólendi við Blöndulón. Náttúrufræðingurinn 78:125-137

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 33:191-203

Weinstein P, Horwell CJ, Cook A (2013) Volcanic Emissions and Health. In: Selinus O (ed) Essentials of Medical Geology: Revised Edition. Springer Netherlands, Dordrecht, pp 217-238.

Zobel DB, Antos JA (1997) A decade of recovery of understory vegetation buried by volcanic tephra from Mount St. Helens. Ecological Monographs 67:317-344

Zobel DB, Antos JA (2007) Flowering and seedling production of understory herbs in old-growth forests affected by 1980 tephra from Mount St. Helens. Botany 85:607-620

Appendix A

Author contributions to the papers

Fieldwork for the Stóra-Búrfell core was carried out by Guðrún Gísladóttir, Egill Erlendsson, Ólafur Eggertsson and myself. I performed magnetic susceptibility measurements (MS) on the core. Egill Erlendsson performed dry bulk density easurements (DBD) on the same core. I, along with Egill Erlendsson subsampled the core. The plant macrofossil analysis was made by me. I sampled the core for radiocarbon material and picked out macrofossils for radiocarbon dating. Ólafur Eggertsson identified the wood found in the core.

I Measured MS, DBD, organic matter (OM) in the Bungutjörn core, I sampled the core for macrofossils and bulk sediments for radiocarbon dating. I subsampled the core for macrofossil samples and performed the macrofossil analysis. I subsampled the core for macrofossil samples and analysed. I subsampled the core for tephra layers and cleaned the samples. Egill Erlendsson mounted and analysed the tephra samples.

Labwork and pollen analysis for comparisons of different pollen preparation methods were made by me.

The fieldwork for the Kagaðarhóll core was carried out by Guðrún Gísladóttir, Egill Erlendsson, Ólafur Eggertsson and myself. I made MS, DBD and OM measurements of the cores. I sampled the cores for macrofossils for radiocarbon dating. I subsampled the cores for pollen analysis, prepared the pollen samples for analysis and analysed them. I subsampled the core for macrofossil samples and analysed the samples. I subsampled the core for tephra layers. Egill Erlendsson cleaned, mounted and analysed the tephra samples. The data analysis was made by me and I wrote the manuscript. Co-authors and anonymous reviewers provided valuable comments and suggestions that helped improve the manuscript.

The fieldwork for the Barðalækjartjörn core was carried out by Guðrún Gísladóttir, Egill Erlendsson, Höskuldur Þorbjarnarson, Þorsteinn Jónsson and myself. I made MS measurements on the cores. Leone Tinganelli made DBD and OM measurements on the sediments and sampled and prepared samples for C/N analysis. I sampled the cores for macrofossils for radiocarbon dating. I subsampled the cores for pollen analysis, prepared the pollen samples for analysis and analysed them. I subsampled the core for macrofossil samples and analysed. I subsampled the core for tephra layers. Egill Erlendsson cleaned, mounted and analysed the tephra samples. The data analysis was made by me and I wrote the manuscript. Co-author, anonymous reviewers and the journal editor provided valuable comments and suggestions that helped improve the manuscript.

I subsampled the cores for pollen analysis in higher resolution around the Hekla 4 tephra in the Kagaðarhóll and Barðalækjartjörn cores. I prepared the pollen samples for analysis and analysed them. The data analysis was made by me and I wrote the manuscript. Co-authors and anonymous reviewers provided valuable comments and suggestions that helped improve the manuscript.