Landscape change in the Icelandic highland: A long-term record of the impacts of land use, climate and volcanism

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ABSATRACT

Agriculture has been practiced in Iceland since settlement (*landnám*; AD 877). This has caused changes in vegetation communities, soil erosion, desertification and loss of carbon stocks. Little data exist regarding vegetation and ecosystems in the Icelandic highland before *landnám* and therefore the impact of land use over time is poorly understood.

The objectives of the study are to examine the timing, nature and causes of land degradation in the highland of Northwest Iceland. Specifically, to determine the resilience of the pre-*landnám* highland environment to disturbances (i.e. climate cooling and volcanism) and whether land use pressure was of sufficient magnitude to facilitate ecosystem change.

A sediment core was taken from the highland lake Galtaból. A chronology for the core was constructed using known tephra layers and radiocarbon dated plant macrofossils. Pollen analysis (vegetation), coprophilous fungal spores (proxy for grazing), and sediment properties (proxies for erosion) were used to provide a high-resolution, integrated vegetation and paleoenvironmental reconstruction.

The pre-*landnám* environment showed resilience to climate cooling and repeated tephra fall. Soon after *landnám* the vegetation community changed and instability increased, indicated by changes in sediment properties. The pollen and spore record suggest introduction of grazing herbivores into the area after *landnám*. Following *landnám*, indicators of soil erosion appear in the sediment properties. Intensification of soil erosion occurred during the 17th century.

The Galtaból record clearly demonstrates what can happen in landscapes without adequate management of natural resources and underestimation of landscape sensitivity. Introduction of land use resulted in changes in vegetation communities, loss of resilience and onset of increased soil erosion. Paleoenvironmental reconstructions may inform future decisions on management of the highland by providing baselines for natural variability in the pre-*landnám* environment.

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1. Introduction

Few places on Earth have been as radically transformed by humans within a span of a few centuries as Iceland. Prior to Norse settlement (*landnám*) in the late 9th century AD, the Icelandic environment was characterised by wetlands, woodlands and shrub heath in lowland areas (e.g. Eddudóttir et al., 2015; Hallsdóttir, 1995; Hallsdóttir and Caseldine, 2005; Roy et al., 2018), while much of the highlands sustained shrublands/woodlands and heath (Eddudóttir, 2016; Wastl et al., 2001). Evidence from lake sediment cores and soil profiles indicate a relatively stable environment during the Holocene prior to *landnám* (Eddudóttir et al., 2016; Streeter et al., 2015; Tinganelli et al., 2018), with changes in vegetation communities and environmental stability driven by climate (Caseldine and Hatton, 1994; Caseldine et al., 2006; Eddudóttir, 2016; Eddudóttir et al., 2015; Hallsdóttir, 1995; Hallsdóttir and Caseldine, 2005) and large tephra-fall events (Eddudóttir et al., 2017).

In this pristine island ecosystem, the settlers initiated a decentralised system of agriculture primarily based on animal husbandry, in which full use was made of land and resources. Hayfield management was widely practiced and cereals were cultivated in at

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least some places (e.g. Riddell et al., 2018a). Further afield, lowland pastures were exploited for both transhumance and free browsing of livestock. Dairy products were prioritised in this agricultural system and the early Icelanders kept a relatively low sheep-to-cattle ratio. The emphasis on milk production meant that livestock was kept close to farms during the milking period in the summer months (Thórhallsdóttir et al., 2013). Zooarchaeology and historical research indicate that sheep became increasingly important over the course of the centuries, particularly after the "Black Death" in the 15th century (Dugmore et al., 2005; Júlíusson, 2018; McGovern et al., 2007; Riddell et al., 2018b). As sheep can be grazed outdoors for much of the year, such changes may have altered grazing pressures on the landscape. Paleoenvironmental studies indicate that the pastoralist agriculture, in particular the increased emphasis on sheep rearing, in conjunction with removal of trees, is largely responsible for the dramatic degradation of soils and vegetation that is evident in Icelandic paleoenvironmental research (e.g. Dugmore et al., 2009; Thórhallsdóttir et al., 2013; Tinganelli et al., 2018). Of importance here is that the *landnám* and following centuries belong to a climate regime commonly known as the Medieval Climate Optimum (MCO) (e.g. Hughes and Diaz, 1994). Later, as climatic deterioration set in with the onset of the Little Ice Age (LIA) (AD 1250/1500−1900; Mann, 2002), disentangling the roles of climate and land use in the process of land degradation becomes more complex. For example, cooling and increased storminess after AD 1500 (Mayewski et al., 1997) occurred in parallel with increased emphasis on sheep farming (Júlíusson, 2018). The general pattern of erosional processes shows an early settlement impact in upland settings that subsequently encroached on lower regions (Dugmore et al., 2009). Additionally, thresholds for lowland soil erosion in South Iceland were passed during the 16th century (Streeter et al., 2012). Changing market demands during the 19th century shifted the emphasis from milk to meat. This led to a substantial increase in sheep numbers from the 19th century to the present, with the highland providing prime grazing areas (Thórhallsdóttir et al., 2013). This is also believed to have led to considerable enhancement of soil erosion and desertification, particularly in highland areas (Arnalds, 2001; Júlíusson, 2018).

It is estimated that from the time of *landnám,* about 120−500 million tonnes of carbon (C) have been lost from Iceland due to soil erosion, of which about half may have become oxidised and escaped into the atmosphere (Óskarsson et al., 2004). In addition to the loss of vegetation cover and carbon stocks, the resulting unstable surfaces are prone to sandstorms (Arnalds, 2015). Today over 43,000 km^2 (42%) of the surface of Iceland is classified as desert and about 22,000 km^2 are sandy deserts that are subjected to active aeolian processes (Arnalds et al., 2016). Many desert areas are created by natural processes, for example by glacial, glaciofluvial and fluvial activity and, directly or indirectly, by climate change. Even though deteriorating climate from the mid-Holocene precipitated erosional processes in the highland (e.g. Ólafsdóttir and Guðmundsson, 2002), a large proportion of these deserts in the interiors formed after *landnám* (e.g. Arnalds, 2015; Dugmore et al., 2009; Greipsson, 2012). Currently, about 34 dust days occur on average per year in Iceland, while dust haze and resuspension of volcanic ash additionally affect the country (Dagsson-Waldhauserova et al., 2014). The unstable nature of large areas of Iceland can therefore exacerbate environmental impacts of catastrophic events such as volcanic eruptions (Arnalds et al., 2013; Cutler et al., 2016a, 2016b; Eddudóttir et al., 2017). The carbon-rich volcanic soils (Andosols) that characterise Iceland are very susceptible to erosion, and soil erosion has been a severe problem in Iceland since settlement. The lack of cohesion of silt-sized particles

in the soils make them susceptible to wind erosion. Due to the large water-holding capacity of andic soils, water can be easily released upon disturbance or saturation. These qualities contribute to the common occurrence of landslides in Iceland and lead to soil erosion by water. Therefore, soil erosion may occur both during dry and wet periods in Iceland (Arnalds, 2015).

The central Icelandic highland is an uninhabited plateau of low arctic tundra (Köppen, 1931) and the climate of the highland is considerably harsher than the cold temperate climate of lowland areas. Glaciofluvial outwash plaines, glaciers and mountains cover much of the highland and large parts are classified as desert, despite a relatively humid climate (Arnalds, 2015). Areas of severe or very severe erosion are common, particularly in active volcanic zones (Arnalds et al., 2001). Yet most of the highland is used as a common summer grazing area for sheep, with grazing rights in specific areas for each local community (Arnalds and Barkarson, 2003). This has led to debate about the relationship between sheep grazing and erosion in Iceland. This debate suffers from a lack of data on the highland vegetation and ecosystems before *landnám* and the impacts that human settlement and agriculture have had on the area over the course of human occupation. No high-resolution vegetation reconstructions exist from the central highland, therefore the impact of human activities since settlement are not well known. To date, data from archaeology, history and paleoecology mainly inform current knowledge of land use and environmental processes in lowland regions (i.e. below 400 m a.s.l.). Aside from the general assumption that lambs separated from ewes were herded to highland pastures, little is known about the use of the highland as agricultural land in the past. This represents a serious gap in knowledge regarding relationships between land use and environmental processes, particularly when considering the large spatial extent of highland areas above 400 m a.s.l. (over half of the island) and that they suffer the greatest erosion within Iceland.

In this research, we examine the timing, nature and causes of land degradation in the highland of Iceland. We seek to answer the following questions: 1) What were the impacts of disturbances such as climate cooling and volcanic activity in the pre-*landnám* highland environment? 2) Was land use pressure of sufficient magnitude to cause a change in vegetation communities, a decrease in vegetation cover, and subsequently soil erosion in the highland during the MCO? 3) Did the LIA initiate or precipitate erosional processes? 4) Did greater emphasis on sheep-rearing after AD 1500 reach into the highland, causing increased soil erosion? To answer these questions we present the first high-resolution, integrated vegetation and paleoenvironmental reconstruction from the highland environs of Iceland. Pollen analysis (vegetation), coprophilous fungal spores (as a proxy for grazing) and sediment properties (proxies for erosion) provide a holistic base from which the dynamics of the natural highland ecosystem, and the impacts posed on the ecosystem by land use, can be examined. This study improves our understanding of the timing, nature and causes of land degradation in the highland of Iceland and enlightens the debate about the current and future use of the Icelandic highland and comparable arctic and alpine environs.

2. Regional setting

Lake Galtaból (65° 15.905′N, 19° 43.596′W) is located on the common rangeland Auðkúluheiði in the Austur-Húnavatnssýsla district, Northwest Iceland. The lake is situated at an elevation of ~460 m a.s.l. (Fig. 1). It is ~1.7 km^2 in area and about 6−10 m deep. Auðkúluheiði has a relatively extensive vegetation cover compared with other highland areas in Iceland (Gísladóttir et al., 2014) and
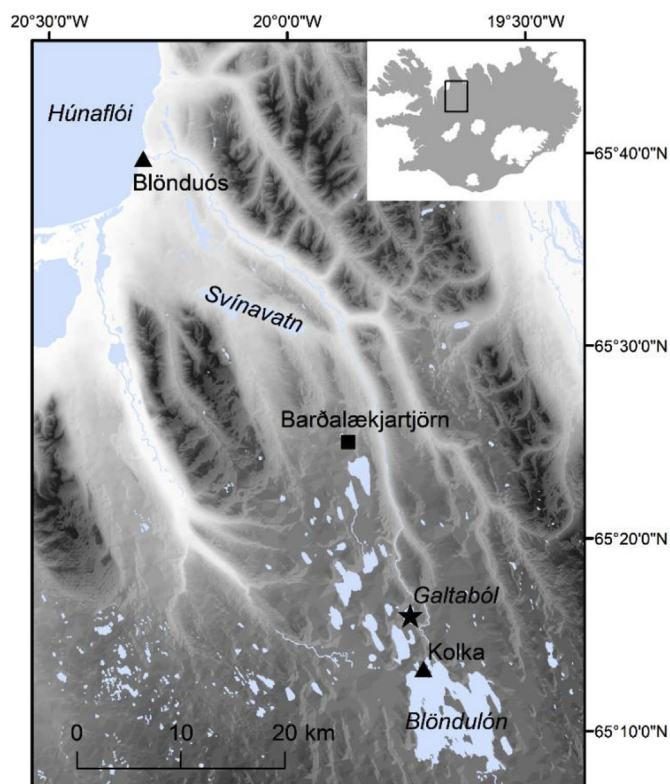
Fig. 1. Map showing the location of Galtaból and other sites mentioned in the text in Northwest Iceland. Galtaból study site (star), weather stations (triangles) and lake Barðalækjartjörn (square).

has been used for summer grazing for centuries (Jónsdóttir, 1984; Magnússon et al., 1992). The soils in the area are Andosols (Arnalds, 2015). Lake Galtaból is surrounded by *Betula nana*-dominated heath, sedge and brown-moss fens with patches of *Salix* scrub, as well as moss snowbed communities (Icelandic Institute of Natural History, 2017). Large patches of sparsely or unvegetated land are found around the lake and there is an extensive network of soil escarpments (rofabörð) on Galtabólsbunga hill east of the lake. More eroded surfaces are found east of the river Blanda (Fig. 2). The soils in the area have been extensively eroded in past centuries (Guðbergsson, 1996).

Weather observations are available for the years 1994−2014 from the Kolka weather station, located 5 km south of Galtaból (Fig. 1, Table 1). It should be noted that the mean tritherm (mean June, July and August) summer temperature for the period, ~7.8 °C, is above the temperature limit for birch tree growth in Iceland (7.2 °C; Jónsson, 2005; Wöll, 2008); however, no natural birch woodlands are found in the area.

3. Materials and methods

In 2015, sediment cores were retrieved from the centre of Galtaból (water depth 840 cm) using a Livingstone piston corer fitted with a Bolivia adaptor and 75 mm diameter polycarbonate tubes. A series of overlapping cores was used to construct a continuous sequence using visible tephra layers and changes in magnetic susceptibility (MS) (Supplementary Fig. 1). Sediment characteristics were described according to the Troels-Smith system (Aaby and Berglund, 1986) (Supplementary Table 1).

Measurements of magnetic susceptibility (MS) were made every 0.5 cm on split core segments using a Geotek Core logger equipped with a Bartington point sensor (MS2E) (Dearing, 1994). Measurements of organic matter (OM) and dry bulk density (DBD, g cm^{-3}) used 1.2 cm^3 of sediment, extracted at 1 cm contiguous intervals. Organic matter (by loss on ignition) was measured by combusting the sediment at 550 °C for 5 h (Bengtsson and Enell, 1986). Dry bulk density was calculated by dividing the dry weight of a sample by the volume of the undisturbed sample (Brady and Weil, 1996). Tephra layers were identified visually and from changes in MS, DBD and OM. Samples consisting of mainly pristine volcanic glass shards >90 μm sieve were mounted on slides, polished and carbon coated. Major element analyses were performed using a JEOL JXA-8230 electron probe microanalyser at the University of Iceland. For most analyses acceleration voltage was 15 kV, beam current 10-nA and beam diameter 10 μm. For silicic, small grained and highly crystallised 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 measured before and after each session of analysis. The data set was inspected for, and cleaned of, anomalies and analyses with sums of <97% (Supplementary Table 2).

The chronology for the Galtaból core (Fig. 3) was constructed by combining tephrochronology and radiocarbon dating. The age−depth model for the core is based on previously dated tephra layers (Table 2; Supplementary Table 2) and radiocarbon-dated macrofossils (Table 3). A smooth spline age-depth model (Fig. 3) was constructed using the R package clam (Blaauw, 2010). Ages are given in calibrated years before present (cal yr BP). According to the 95% confidence of the age model, the age uncertainty is lowest ≤±10 yrs after c. 330 cal yr BP and highest ±180−186 yrs between c. 1740−2140 cal yr BP. The temporal resolution of the core is 6−15 yr cm^{-1}, lowest 10−15 yr cm^{-1} 3300-1000 cal yr BP and highest 6−10 yr cm^{-1} 300-100 cal yr BP.

Samples for pollen analysis were taken every 8 cm. Samples of 2 cm^3 volume were prepared using standard chemical methods: 10% HCl, 10% NaOH, 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}). One *Lycopodium clavatum* spore tablet (batch no. 177745) was added to each sample (Stockmarr, 1971) to enable calculations of pollen accumulation rates (PAR; grains cm^{-2} yr^{-1}). A minimum of 300 indigenous terrestrial pollen grains, total land pollen (TLP), were counted for each sample. Identification of pollen grains and spores was based on Moore et al. (1991) and a pollen type slide collection belonging to the Icelandic Institute of Natural History. Pollen and spore taxonomy followed Bennett (2007), with special amendments specific to the Icelandic pollen flora according to Erlendsson (2007). Pollen categories and calculations followed Hallsdóttir (1987) and Caseldine et al. (2006). Measurements of *Betula* pollen diameters were made at 1000x magnification. The pollen diameters of *Betula nana* have been shown to be significantly smaller than those of *Betula pubescens*, with a mean diameter of 17.31 (SD = 0.88) for *Betula nana* and 25.19 (SD = 1.65) μm for *Betula pubescens* ssp. *tortuosa* in samples from Finnish Lapland (Mäkelä, 1996). However, measurements in Iceland have shown that there is an overlap in pollen diameters of the two species (Karlsdóttir, 2014). A two tailed z-test was performed to determine if there was a statistically significant difference in *Betula* pollen diameters before and after *landnám*. Occurrences of non-triporate *Betula* pollen grains were also noted, as these can indicate hybridisation between *B. nana* and *B. pubescens* (Karlsdóttir, 2014). Pollen and macrofossil diagrams were constructed using Tilia (version 2.1.1). Deteriorated pollen grains of *Betula* and Poaceae were recorded, as they can indicate reworking of pollen (Havinga, 1967, 1971). The pollen data were divided into pollen assemblage zones (PAZs) using
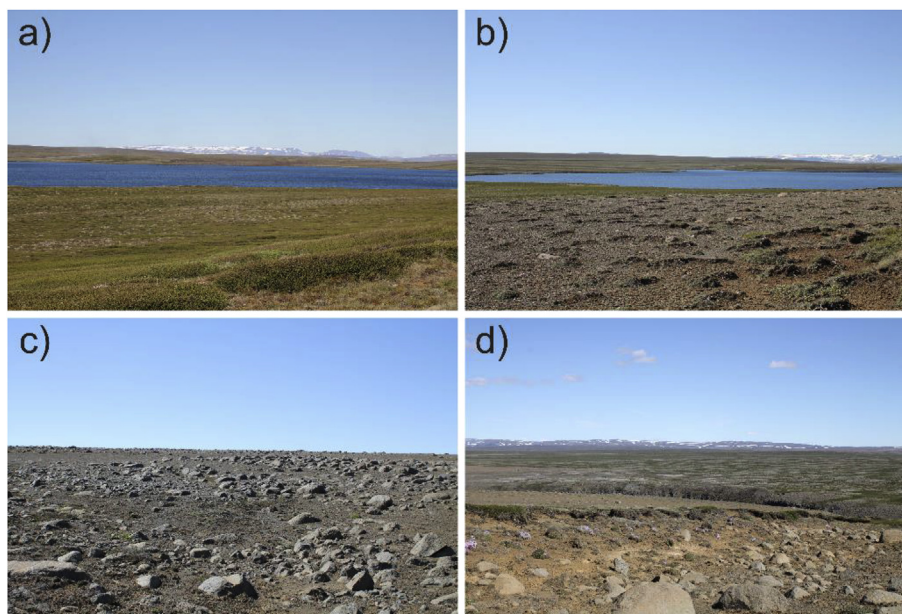
Fig. 2. Galtaból and its surroundings: a) Lake Galtaból, b) view of Galtaból from Galtabóĺsbunga, with signs of soil erosion in the foreground, c) sparsely vegetated areas of soil erosion on the eastern side of Galtabóĺsbunga, d) soil escarpments and exposed soil on the eastern side of Galtabóĺsbunga.

Table 1
Meteorological data from Kolka weather station (unpublished data from the Icelandic Met Office).

Period	1994−2014
Elevation	505 m a.s.l.
Mean tritherm temperature	~7.8 °C
Mean July temperature	~8.8 °C
Mean January temperature	~-4.4 °C[a]
Mean annual precipitation[b]	~398 mm per year[c]

Unpublished data from the Icelandic Met Office.
[a] Data missing for 1994, 1996 and 2010.
[b] Mean rainfall 1982−2003.
[c] Data missing for 2003, 2004,2008, 2010 and 2011.

CONISS cluster analysis of terrestrial pollen in Tilia (Fig. 4) (Grimm, 2016).

Subsamples of 1 cm thickness were taken every 4 cm for measurements of total carbon (TC), total nitrogen (TN) and $\delta^{13}C$ and $\delta^{15}N$ stable isotope ratios of bulk sediments. The samples were dried at 50 °C, homogenized using a ball mill and sieved through a 150 μm mesh. A total of 100 samples were analysed for this study. The carbon, nitrogen and isotope measurements were performed on a Thermo Delta V isotope ratio mass spectrometer at the Cornell University Isotope Laboratory. The contribution of inorganic carbon to TC in Icelandic lake sediments is considered small (e.g. Harning et al., 2018; Langdon et al., 2010; Larsen et al., 2012) as there is no carbonate bedrock (Jóhannesson, 2014). Although dissolved inorganic carbon (DIC) has been measured in rivers in Iceland (Kardjilov et al., 2006), the amounts of inorganic carbon measured in soils from the southern highland are negligible (Mankasingh and Gísladóttir, 2019). Therefore, changes in TC in the sediments are considered to reflect changes in total organic carbon (TOC).

Ordination methods were performed using the R package vegan (Oksanen et al., 2016). Detrended correspondence analysis (DCA) was performed on the pollen dataset. A first axis length of 1.1563 suggests a linear response in the dataset; therefore, principal component analysis (PCA) was preferred. PCA was performed on Hellinger-transformed data, which included terrestrial pollen taxa
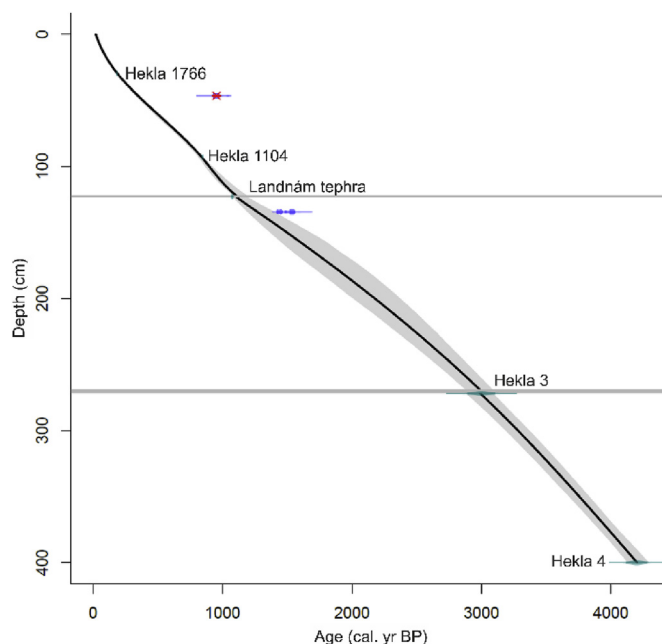

Fig. 3. Age-depth model for the Galtaból core.

and coprophilous fungal spores with abundances >1%. PCA was also performed on a standardised dataset of organic matter and physical properties of sediments (TC, TN, OM, MS, DBD, $\delta^{13}C$ and $\delta^{15}N$).

4. Results

4.1. Lithology

The sediments below the Hekla 3 tephra layer (c. 3000 cal yr BP; Dugmore et al. (1995)) consist of silty gyttja with some fine sand interspersed with tephra layers. Above the tephra, sand constitutes a larger proportion of the sediment (Supplementary Table 1).

Table 2
Tephra layers used for constructing the age-depth model for the Galtaból core.

Tephra layer	Depth (cm)	Age cal yr BP ± 2σ	Tephra thickness (cm)	Tephra boundary	Reference
Hekla 1766	29.5	184	0.1	Unclear[a]	þórarinsson (1968)
Hekla 1104	92.5	846	0.1	Unclear[a]	þórarinsson (1968)
Landnám tephra	122	1073 ± 1	1	Clear	Schmid et al. (2017)
Hekla 3	272	3000 ± 50	3	Clear	Dugmore et al. (1995)
Hekla 4	402.5	4200 ± 40	3	Clear	Dugmore et al. (1995)

[a] Presence of tephra identified by peaks in MS and DBD.

Table 3
Radiocarbon-dated macrofossils used to construct the age-depth model for the Galtaból core.

Sample no.	Depth (cm)	^{14}C age ± 1σ	δ^{13}C (‰)	Age cal yr BP (2σ)	Material
ETH-87400	46.5	1044 ± 22	−27.1	981−926	Mosses: Racomitrium aviculare, Calliergonella cuspidata
ETH-87401	134.5	1619 ± 23	−31.2	1562−1416	Betula nana leaf
ETH-87403[a]	429.5	4144 ± 22	−24.5	4820−4581	Mosses: Sphagnum sp.

[a] Radiocarbon date ETH-87403 was not used in the age-depth model as it is below Hekla 4, which here forms the base of the paleoenvironmental record.

4.2. Pollen assemblage zones

The pollen record covers the period c. 4200−100 cal yr BP and is divided into three pollen assemblage zones (Fig. 4).

4.2.1. PAZ 1 (4200−2800 cal yr BP)

The pollen assemblage in PAZ 1 is dominated by *Betula* pollen (43−64% of TLP). *Salix* makes up 5−13% of TLP, Cyperaceae ranges between 10 and 19% of TLP and Poaceae decreases upwards within the PAZ from ~17 to 6% of TLP. Herb pollen include *Angelica archangelica* and *A. sylvestris,* with a relative abundance of <1% of TLP, *Oxyria digyna* at ≤2% of TLP, *Ranunculus acris*-type at ≤1.6% of TLP and *Rumex acetosa* at ≤1.6% of TLP. Few pollen associated with aquatic plants are present in this PAZ, save for *Myriophyllum alterniflorum*, which makes up 0.3−1.7% of pollen and spores. However, spores of *Isoetes echinospora* increase upwards within the PAZ from ~5.6 to >16% of pollen and spores (Fig. 4). The highest PAR for *Betula* of >500 grains cm^{-2} yr^{-1} is recorded within this PAZ. The *Salix* PAR is 45−128 grains cm^{-2} yr^{-1} and decreases upwards, while the *Juniperus communis* PAR is variable and ranges between 6 and 41 grains cm^{-2} yr^{-1} (Fig. 5). The mean *Betula* pollen grain diameter is 20.76 ± 1.28 μm (Fig. 6).

4.2.2. PAZ 2 (2800−1000 cal yr BP)

There is little change in the main pollen types from PAZ 1. *Betula* pollen is 40−63% of TLP and Cyperaceae pollen is 9−19% of TLP. Poaceae pollen increase again and range between 7 and 18% of TLP. *Plantago maritima* and *Potentilla*-type pollen appear in this PAZ, along with *Rhinanthus*-type pollen. *Silene vulgaris*-type pollen are recorded more frequently within this PAZ but remain ≤1% of TLP. There is a small increase in pollen of *Thalictrum alpinum* from 5 to 6% at the top of PAZ 1 to 6−15% of TLP within this PAZ. *Myriophyllum alterniflorum* pollen all but disappear, however *Isoëtes echinospora* spores increase and peak at ~33−44% of pollen and spores c. 1750−1300 cal yr BP. *Lycopodium annotinum* spores increase to 1−2% of pollen and spores (Fig. 4). The *Betula* PAR decreases to 200−400 grains cm^{-2} yr^{-1}, and the *Salix* PAR decreases as well to 20−49 grains cm^{-2} yr^{-1}, *Juniperus communis* decreases to <19 grains cm^{-2} yr^{-1} (Fig. 5). The mean *Betula* pollen grain diameter is 21.27 ± 1.59 μm (Fig. 6).

4.2.3. PAZ 3 (1000−100 cal yr BP)

Betula decreases sharply to ~24−27% of TLP in PAZ 3; this decrease continues upward within the PAZ to a relative abundance of <20% of TLP after c. 200 cal yr BP. *Juniperus communis* decreases as well and is 0−1% of TLP in this PAZ. Pollen of Ericales, *Empetrum nigrum* and *Vaccinium*-type increase, with >3% *Empetrum nigrum* at c. 800 cal yr BP and >1% *Vaccinium*-type pollen of TLP. Cyperaceae increases to above 21% of TLP at ~1000 to 400 cal yr BP. *Angelica* spp. pollen mostly disappear from the record after c. 1000 cal yr BP. *Galium* pollen that are only sporadically recorded earlier increase to >0.7% of TLP. *Thalictrum alpinum* pollen increase and are >19% of TLP. *Isoëtes echinospora* spores decrease again to <15%, apart from a peak of ~22% at c. 400 cal yr BP. *Sporormiella*-type fungal spores increase c. 800 cal yr BP (Fig. 4). The *Betula* PAR decreases further within this PAZ to 140−320 grains cm^{-2} yr^{-1}, and the *Juniperus communis* PAR decreases to 0−9 grains cm^{-2} yr^{-1}. PARs of *Empetrum nigrum* and *Vaccinium*-type increase at c. 900 cal yr BP to 14−66 grains cm^{-2} yr^{-1} and 11−46 grains cm^{-2} yr^{-1}, respectively. Cyperaceae and Poaceae PARs also increase c. 900 cal yr BP and 800 cal yr BP, respectively. The coprophilous fungi accumulation rate increases, especially for *Sporormiella*-type to 8−49 spores cm^{-2} yr^{-1} after c. 800 cal yr BP (Fig. 5). The mean *Betula* pollen grain diameter is 19.81 ± 1.43 μm within this PAZ, smaller than in PAZ 2 (Fig. 6; Table 4).

4.2.4. Principal component analysis of pollen data

The first PCA axis accounts for 56.5% of the variance in the dataset and the second axis for 6.1%. *Betula, Salix* and *Juniperus communis* are the most important pollen types in PAZ 1 and 2. Herbs such as *Angelica archangelica*, *A. sylvestris* and *Rumex acetosa* influence the dataset in PAZ 1, while *Oxyria digyna* and *Ranunculus acris*-type pollen are important in PAZ 2. In PAZ 3, pollen of the dwarf shrubs *Empetrum nigrum*, *Vaccinum* and Ericales become more important along with the herbs *Thalictrum alpinum*, *Silene vulgaris*-type and *Galium*, grasses (Poaceae), sedges (Cyperaceae) and coprophilous fungal spores of *Sporormiella*-type and *Sordaria*-type (Fig. 7).

4.2.5. Organic matter and physical properties

The Hekla 4 tephra layer is 3 cm thick and well defined within the stratigraphy of the core. The values above the Hekla 4 tephra layer (c. 4200 cal yr BP) are relatively stable with TC between 6.7 and 12%, TN 0.7−1.1%, OM 14.3−24.7% and C/N ratio between 11.1 and 12.3, excluding major tephra layers. MS and DBD values are relatively low with DBD of 0.21−0.24 g cm^{-3} (excluding values for tephra layers). Above the Hekla 3 tephra layer, the values become more variable due to tephra deposits in the sediments between
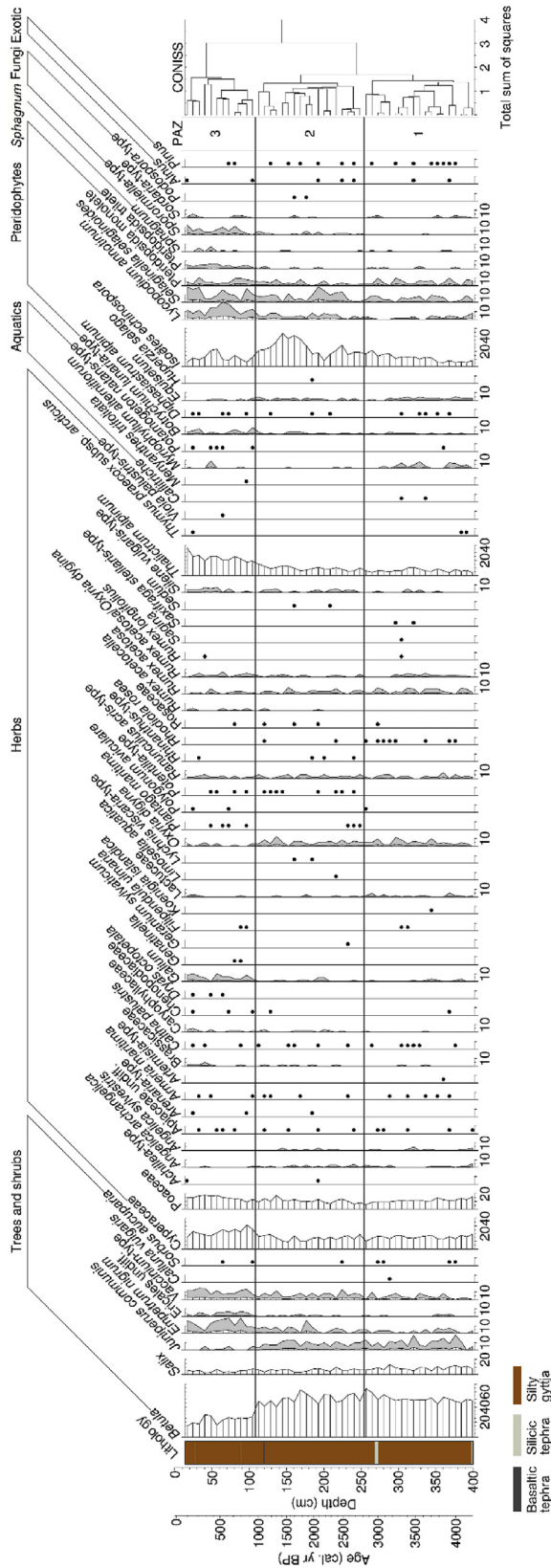
Fig. 4. Pollen percentage diagram for the Galtaból core. Division into pollen assemblage zones (PAZ) was made using CONISS. Grey curves represent x5 exaggeration. Dots denote pollen taxa with presence <1 of TLP %.

Hekla 3 and the Landnám tephra (c. 877 AD), indicated by peaks in MS and DBD and corresponding dips in organic proxies. Between Hekla 3 and the Landnám tephra, TC ranges between 6 and 13.3%, TN 0.6–1.3% and the C/N ratio 9.7–12.3. Stable isotope ratios of $\delta^{13}C$ range between −16 and −18.9‰ c. 4200–1000 cal yr BP and $\delta^{15}N$ stable isotope ratios range between 0 and −1.2‰. The largest change in the organic proxies occurs above the Landnám tephra as the TC drops to <6.3%, TN <0.8%, OM <15% and $\delta^{13}C$ stable isotope ratios decrease to <−19‰. These shifts to lower values are permanent for the remainder of the record. The changes in MS and DBD are obscured by the deposition of the Landnám tephra layer. Permanent shifts to higher values of MS and DBD occur c. 1000 cal yr BP, with DBD values >0.24 g cm^{-3}. Stable isotope ratios of $\delta^{15}N$ increase to positive values c. 1000 cal yr BP and continue to increase upwards (Figs. 8 and 9).

4.2.6. Principal component analysis of physical and organic matter properties

The first PCA axis accounts for 66.7% of the variance in the dataset and the second axis for 15.3%. Organic proxies (OM, TC, TN, C/N ratio and $\delta^{13}C$) influence the samples in PAZ 1 and 2, from 4200 to 1000 cal yr BP. After 1000 cal yr BP, changes in the sediment properties such as increases in $\delta^{15}N$ stable isotope ratios and MS influence a shift in the samples (Fig. 10).

5. Discussion

5.1. The pre-landnám environment at Galtaból

The Galtaból record begins above the Hekla 4 tephra layer (c. 4200 cal yr BP; Dugmore et al., 1995), which originated from one of the largest explosive Holocene eruptions in Iceland (Larsen and Thorarinsson, 1977). The tephra was deposited when a cooling climate and expanding glaciers had begun to influence the Icelandic highland environment (e.g. Geirsdóttir et al., 2019) following the warmest period of the Holocene in Iceland, the Holocene Thermal Maximum (HTM) (e.g. Eddudóttir et al., 2015; Eddudóttir et al., 2016; Larsen et al., 2012; Tinganelli et al., 2018). The tephra fall from the Hekla 4 eruption caused short term vegetation changes in the lowlands of Northwest Iceland and, in combination with a cooling climate, may have led to a shift in vegetation communities on Auðkúluheiði (Eddudóttir et al., 2017). Evidence of increased aeolian input in soil profiles and lake sediments are seen in records from the region following the deposition of the tephra (Eddudóttir et al., 2016, 2017; Larsen et al., 2012; Möckel, 2016; Tinganelli et al., 2018). The pollen record from Galtaból shows similarities to an existing, lower-resolution Holocene pollen record from Barðalækjartjörn (Eddudóttir et al., 2016), located about 18 km north of Galtaból (Fig. 1). At Barðalækjartjörn, the Hekla 4 tephra layer serves as a boundary between vegetation communities, as dwarf-shrub heath expanded at the expense of woodland (Eddudóttir et al., 2017). A change in the vegetation composition is evidenced by the appearance of macrofossils of *Betula nana* and *Empetrum nigrum* above the tephra layer in the Barðalækjartjörn sediments, while *Betula pubescens* fruits continue to be recorded (Eddudóttir et al., 2016). The mean *Betula* pollen diameter measured above Hekla 4 (PAZ 1) in the Galtaból sediments (~21 μm; Fig. 6) is similar to those measured in the corresponding period in Barðalækjartjörn. Macrofossils of both *Betula nana* and *Betula pubescens* in the Barðalækjartjörn sediments (Eddudóttir et al., 2016) and the proportion of non-triporate *Betula* pollen of >5% of total *Betula* pollen at both Galtaból (Fig. 5) and Barðalækjartjörn indicate hybridisation between the two *Betula* species (Karlsdóttir, 2014; Karlsdóttir et al., 2008, 2009, 2012). This suggests that the

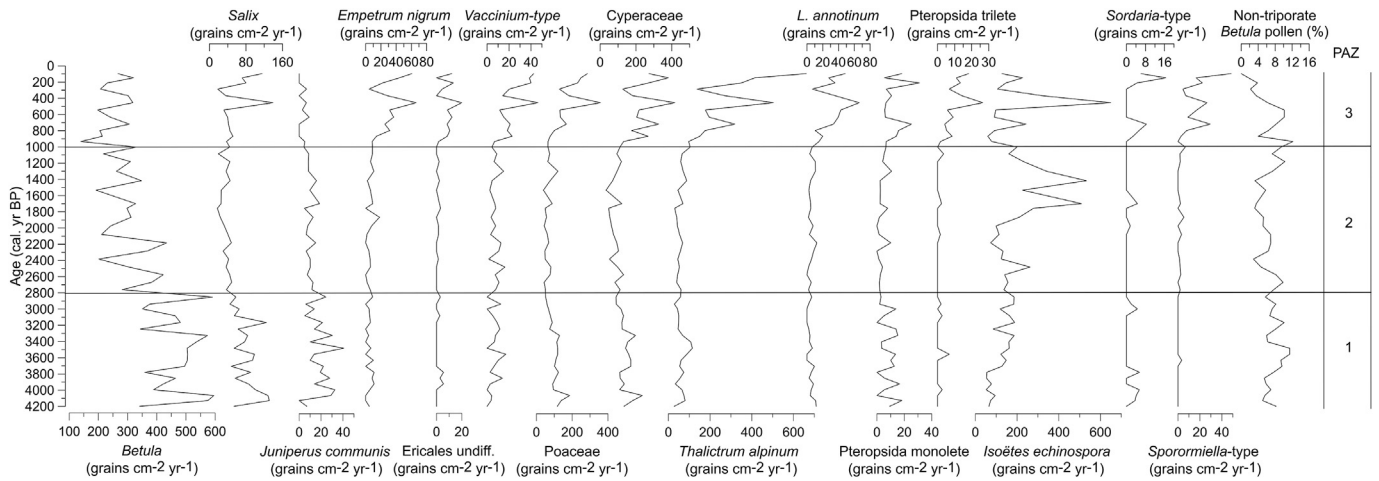**Fig. 5.** Pollen accumulation rates (PAR; grains cm^{-2} yr^{-1}) for selected pollen and spore taxa, and percentages of non-triporate *Betula* pollen.
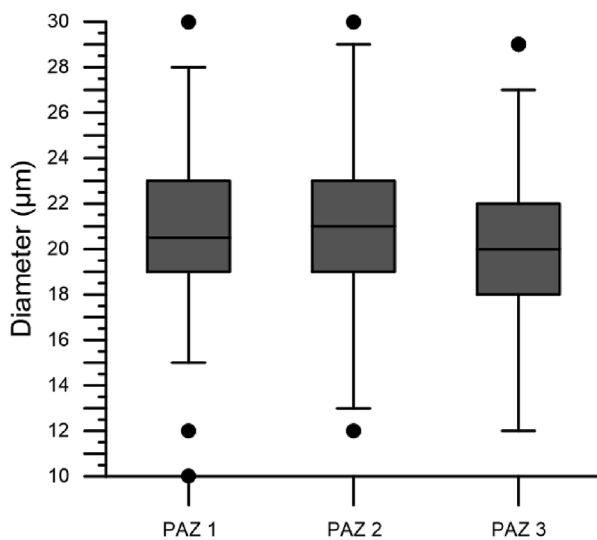

Fig. 6. Boxplot of *Betula* pollen grain diameters for the pollen assemblage zones (PAZs) in the Galtaból record.

Table 4

Results of a two sample z-test, two tailed, comparing the *Betula* pollen diameters before (PAZ 2) and after *landnám* (PAZ 3).

PAZ	n	Mean	SD	z	p
Before *landnám*	431	20.76	3.17	6.34	1.13*10^{-10}
After *landnám*	276	19.81	2.86		

B. nana and *B. pubescens* coexisted in this part of the highland after the Hekla 4 eruption. *Salix* pollen (5–13% of TLP) and sporadic occurrences of pollen of the tree species *Sorbus aucuparia* indicate the persistence of woodland/shrubland in the area around Galtaból within PAZ 1. However, the presence of *Juniperus communis* pollen (0–4% of TLP), pollen of dwarf shrubs *Empetrum nigrum* (0–1.3% of TLP) and *Vaccinium* (0–1.9% of TLP) as well as the herbs *Thalictrum alpinum* (4–11.1% of TLP), *Oxyria digyna* (0–2.3% of TLP) and *Rumex acetosa* (0–1.6% of TLP) indicate the presence of shrub heath (Fig. 4). Interpretation of the pollen data should take into consideration the fact that both *Betula pubescens* and *Betula nana* may be

overrepresented in modern pollen samples from Iceland (Birks, 1973; Rymer, 1973), while other pollen taxa such as *Empetrum nigrum* and *Vaccinium*-type can be underrepresented in pollen assemblages relative to the local presence of the plants (Schofield et al., 2007). The pollen assemblage at Galtaból may therefore indicate a habitat similar to the modern-day Boreo-Atlantic crowberry-bog bilberry birch woods in Iceland, composed of intermittent woodland/shrubland with a very open canopy of low-growing birch and dwarf shrubs such as *Empetrum nigrum*, *Vaccinium uliginosum* and *Betula nana* (Icelandic Institute of Natural History, 2017).

The sedimentary record suggests a relatively stable depositional environment between the deposition of the Hekla 4 and Hekla 3 tephra layers c. 4200 and 3000 cal yr BP, respectively. TC is ≥8% for most of this period and TN is >0.8%, excluding samples near tephra layers. The C/N ratio during this period is 10–12.2, close to values measured for some aquatic and terrestrial plants (Wang and Wooller, 2006) and algae (Florian, 2016) in Icelandic lakes. Stable isotope ratios of δ^{13}C of ~−16 to −20‰ are intermediate between aquatic plants/algae and terrestrial plants/soil (Fig. 9). This suggests that the origin of the organic matter in the sediments is both autochthonous and allochthonous. Only few pollen and spore taxa of aquatic plants are recorded in the Galtaból core, most notably *Isoëtes echinospora*. Changes in relative abundances and PAR of the taxa do not correspond to changes in organic matter proxies and are therefore not useful for interpretation of the organic proxies (Figs. 4 and 5). Several small decreases in organic matter, TC and TN and corresponding increases in DBD and MS occur during the period c. 4000-3500 cal yr BP (Fig. 8). Geochemical analyses of tephra grains at these levels suggest a chemical composition corresponding to the Hekla 4 tephra (Supplementary Fig. 2). This is likely due to reworking of the tephra by wind and/or water. Tephra deposits that are not contained by vegetation can be reworked by wind or water (Arnalds, 2013). This suggests that reworked tephra may have been mobile in the environment for some time after the eruption (e.g. Eddudóttir et al., 2017; Larsen et al., 2012). The eruption of the Hekla volcanic system in south Iceland 4200 cal yr BP (Dugmore et al., 1995) that produced the Hekla 4 tephra was one of the largest explosive Holocene eruptions in Iceland. The eruption is estimated to have produced ~10 km^3 of freshly fallen tephra (Larsen et al., 2015). Although the largest volumes of the tephra were carried north and northeast, the deposits covered most of the country (Larsen and Thorarinsson, 1977). Existing paleoecological reconstructions suggest that the vegetation at higher elevations at
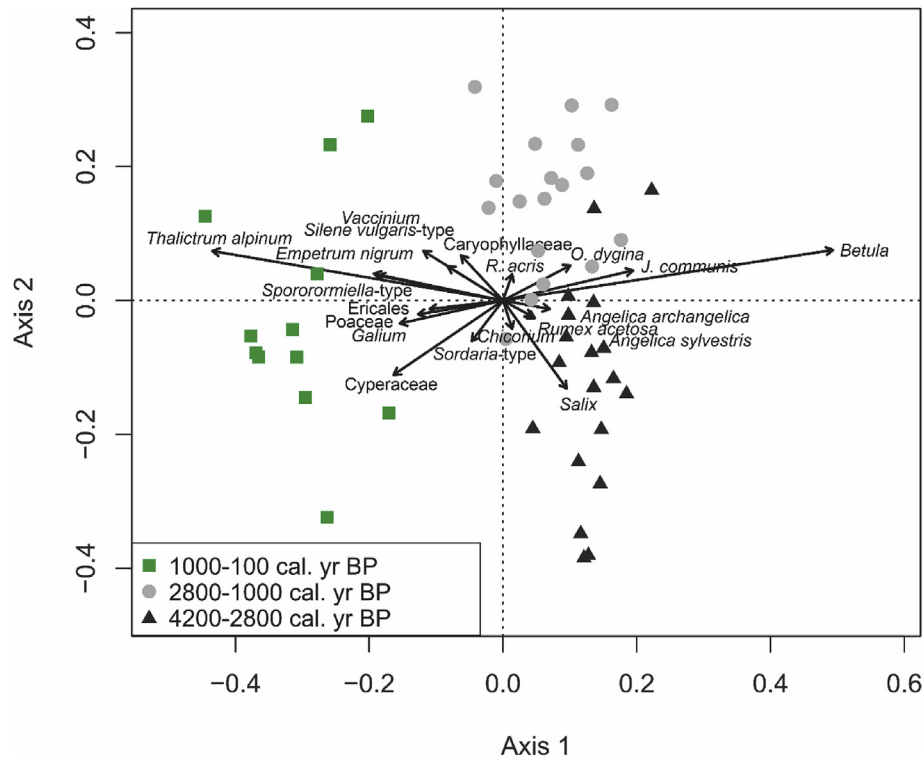
Fig. 7. Principal component analysis of the terrestrial pollen and coprophilous fungal spores from Galtaból. Division of samples into periods is based on pollen assemblage zones.
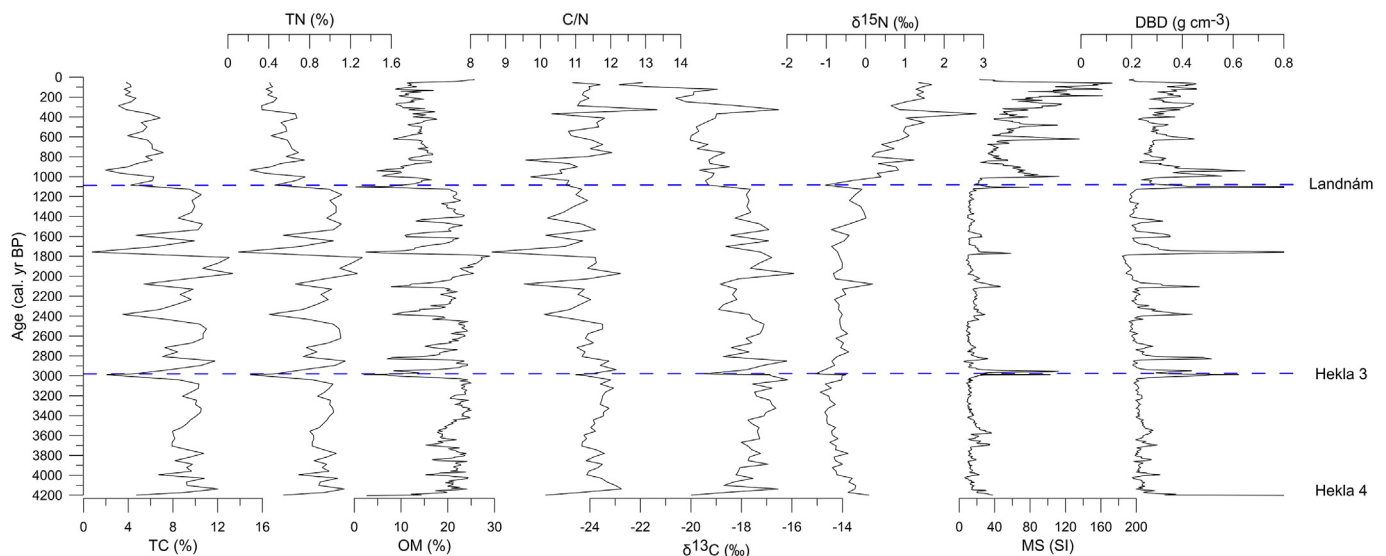

Fig. 8. Organic and physical properties of the Galtaból sediments. Total carbon (TC), total nitrogen (TN), organic matter (OM), carbon nitrogen ratio (C/N), δ^{13}C stable isotope ratios, δ^{15}N stable isotope ratios, magnetic susceptibility (MS) and dry bulk density (DBD).

the time of the eruption was characterised by open woodland, dwarf shrub heath and wetlands (Eddudóttir et al., 2016, 2017; Wastl et al., 2001); these are vegetation communities that are able to effectively trap tephra (e.g. Arnalds, 2015). This may indicate that reworked tephra in the environment in the centuries following the eruption was due to the large volume of tephra deposited in the highland.

Despite the sustained dominance of *Betula* over the period c. 4200−1000 cal yr BP (Fig. 4), the PCA depicts a shift in the pollen

assemblage at c. 2800 cal yr BP (Fig. 7). This is indicated by a decrease in *Salix* pollen, most notably reflected in the PAR of the pollen taxon with values <48.5 grains cm^{-2} yr^{-1} after c. 2800 cal yr BP (Fig. 5). This is accompanied by an increase in pollen of *Silene vulgaris*-type representing two species of *Silene* in Iceland: *Silene acaulis* and *Silene uniflora*. Although both species grow on sandy surfaces, *Silene acaulis* also grows in dry grassland and is today one of the most common plants in Iceland. Pollen of *Plantago maritima* appear at the beginning of PAZ 2; *P. maritima* grows mostly on rocky
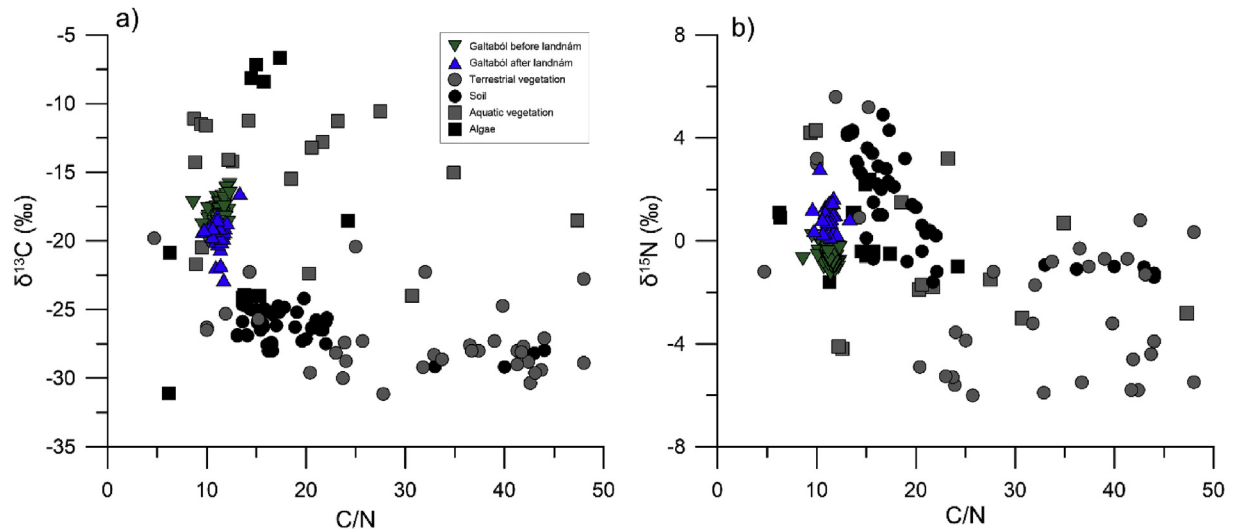
Fig. 9. Organic matter properties of the Galtaból sediments compared with values for Icelandic vegetation, soil and algae (Florian, 2016; Langdon et al., 2010; Skrzypek et al., 2008; Wang and Wooller, 2006). a) Sedimentary $\delta^{13}C$ values and C/N ratios, b) sedimentary $\delta^{15}N$ values and C/N ratios.
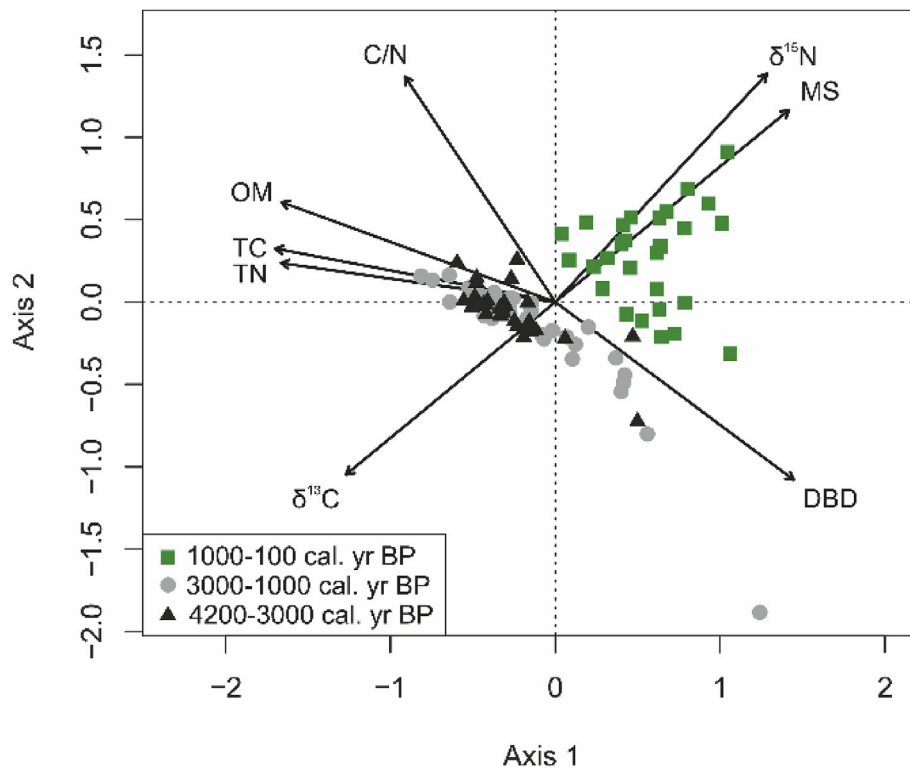

Fig. 10. Principal component analysis of organic and physical properties from the Galtaból sediments. Division of samples into periods is based on pollen assemblage zones.

surfaces but can also be found in grasslands (Kristinsson et al., 2018). A decrease in Poaceae pollen, with a PAR of <90 grains cm^{-2} yr^{-1} from c. 3200 cal yr BP (Fig. 5), indicates that an increase in grassland is unlikely. This change may therefore indicate increased disturbances in the environment, specifically from reworked tephra. Peaks in DBD and MS and larger dips in organic matter, TC, TN and C/N ratio are observed more frequently above the Hekla 3 tephra layer (c. 3000 cal yr BP). A series of tephra layers are recorded in the sediments during this period, however the magnitudes and distribution of tephra in Iceland for these tephra

layers is not known. One possible explanation for the increased tephra deposition after the Hekla 3 eruption is that the environment became less able to hinder the reworking of tephra following subsequent eruptions. Like the Hekla 4 tephra, Hekla 3 represents one of the largest explosive eruptions of the Holocene (Larsen and Thorarinsson, 1977). The eruption coincided with a change to a colder climate and ice cap expansion reflected in several lake records in Iceland (Geirsdóttir et al., 2013). Harsher climate conditions are also reflected in an increase in storminess, indicated by greater concentration of potassium in the GISP2 ice core between
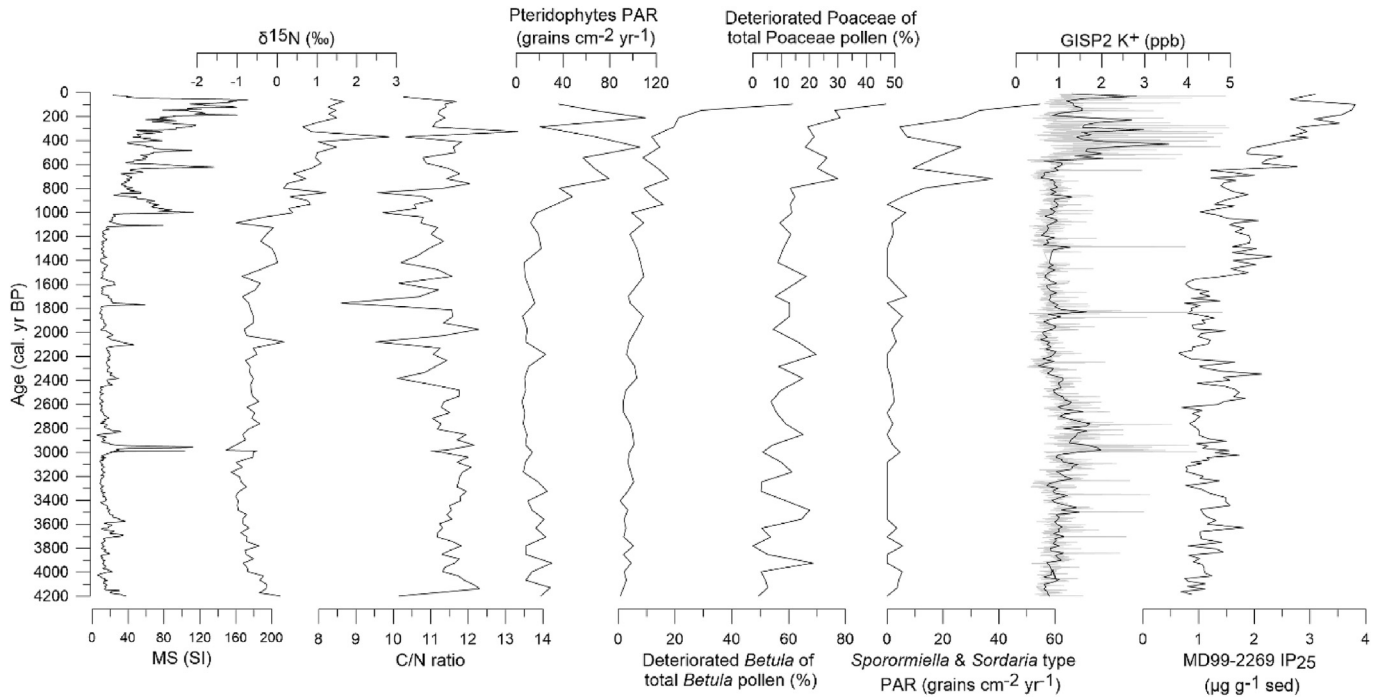
Fig. 11. Comparison of key indicators of erosion in the Galtaból core and climate records from the region. GISP2 ice core potassium (K^{+}), black line represents 20 year average values (Mayewski et al., 1997), IP$_{25}$ biomarker from marine sediment core MD99-2269, north of Iceland (Cabedo-Sanz et al., 2016).

3000 and 2300 cal yr BP (Mayewski et al., 1997) and IP$_{25}$ biomarker inferred drift ice north of Iceland between 2600 and 2200 cal yr BP. A further increase in drift ice is observed north of Iceland at c. 1500 cal yr BP (Cabedo-Sanz et al., 2016) (Fig. 11). Despite pulses of tephra deposited in the lake after Hekla 3, the sediment properties return to similar values above each tephra layer during the pre-*landnám* period: low MS, DBD ~0.2 g cm^{-3}, OM ~18−27%, TC ~8−13% and TN ~1%. The minor changes in the pollen assemblage observed c. 2800 cal yr BP may be a response to the impact of the Hekla 3 tephra layer, a cooling climate recorded c. 3000 cal yr BP (Geirsdóttir et al., 2013, 2019; Larsen et al., 2012) and/or increased disturbances from tephra fall. The pre-*landnám* Holocene vegetation and sedimentary records from Galtaból demonstrate the resilience (engineering resilience, the resistance to disturbances and how quickly a system returns to an equilibrium (O'Neill et al., 1986; Pimm, 1984)) of the natural vegetation surrounding the lake to environmental changes. The stability recorded in the sedimentary record above Hekla 3 highlights how the terrestrial ecosystem was able to recover from repeated temporary disturbances, such as cooling climate and increased tephra in the environment.

5.2. The impact of landnám on the environment at Galtaból

The largest change in the pollen assemblage occurs between c. 1000 and 900 cal yr BP (AD 950−1050). The most marked change is a decrease in *Betula* pollen, with relative abundance decreasing to <30% of TLP in PAZ 3 (Fig. 4). There is a significant change to smaller mean *Betula* pollen diameters after *landnám* (Table 4), with mean diameters <20 μm (Fig. 6); a similar shift to smaller *Betula* pollen diameters is also seen in the Barðalækjartjörn pollen record after c. 1000 cal yr BP (Eddudóttir et al., 2016). The increase in *Betula* pollen with smaller diameters may demonstrate the increased importance of *Betula nana* in the pollen assemblage at the expense of *B. pubescens*. The percentage of non-triporate *Betula* pollen

decreases upwards after c. 400 cal yr BP (Fig. 5), probably indicating decreased hybridisation between *Betula nana* and *B. pubescens* as the latter disappeared from the environment. A shift to heath vegetation is reflected in the PCA of the terrestrial pollen with increased importance of pollen from the dwarf shrubs *Empetrum nigrum* and *Vaccinium* as well as Ericales undiff. pollen. This is accompanied by an increase in *Thalictrum alpinum*, Poaceae and Cyperaceae pollen (Fig. 7). These changes are reflected in the PAR record (Fig. 5), with an increase in Cyperaceae pollen after c. 900 cal yr BP to >176 grains cm^{-2} yr^{-1} and Poaceae >100 grains cm^{-2} yr^{-1} c. 800 cal yr BP. Coprophilous fungal spores, from fungi that are reliant upon herbivores for spore germination (e.g. Cugny et al., 2010), are found in low numbers throughout. It has been suggested that the presence of these spores in paleological records pre-*landnám*, given the absence of mammal herbivores, may be derived from birds (Eddudóttir et al., 2015). Both *Sporormiella* spp. and *Sordaria* spp. spores have been found on bird faeces in Iceland (Hallgrímsson and Eyjólfsdóttir, 2004). However, from c. 800 cal yr BP (AD 1150) an increase in coprophilous fungal spores, particularly *Sporormiella*-type, but also *Sordaria*-type, is recorded. Although coprophilous fungal spores may not serve as a quantitative measures of livestock density near a sampling site and their taphonomy is not fully understood (Davies, 2019), their presence may indicate grazing livestock near the lake.

Pollen of *Juniperus communis* are only occasionally recorded after c. 1000 cal yr BP (Fig. 4); this may be the result of livestock overgrazing as seedlings of the species are sensitive to grazing (Thomas et al., 2007). However, some grazing can be beneficial for the species and an increase in *Juniperus* pollen is considered a grazing indicator in pollen records (e.g. Behre, 1981). Therefore, the complete disappearance of the species may indicate that adult plants that are not palatable (not preferred by grazing animals) were removed as well, possibly felled for firewood, and grazing subsequently prevented regeneration. This may represent the use of the highland as a source of wood in the early centuries after

landnám. Other indications of grazing are the near disappearance of pollen from the palatable, grazing-sensitive genus *Angelica* (*A. archangelica* and *A. sylvestris*; Kristinsson et al., 2018). The nature of land use in the highland at the time of *landnám* has not been widely studied, i.e. the type of livestock that was kept there and grazing practices. Only one archaeological excavation has been made of a highland shieling in Iceland. The shieling at Pálstóftir was located at ~600 m a.s.l. in the eastern highland. It was in use during the 10th and 11th centuries and evidence for jewellery making and hunting were found, suggesting that a wide range of activities took place in the shieling besides transhumance (Lucas, 2008). No such excavations have been made on Auðkúluheiði, however remains of buildings of unknown ages, that may have been shielings have been found c. 6.5 and 11.5 km NNW of Galtaból. They are believed to have been abandoned between AD 1700−1800 (Zoëga and Sigurðarson, 2012).

A permanent shift in sediment properties occurs at the same level as the Landnám tephra c. 1073 cal yr BP (877 AD) (Figs. 8−10). The tephra is 1 cm thick and clearly defined in the core (Table 2). Values of organic matter proxies decrease permanently to TN <0.8%, TC <7.2%, OM <16.8% and δ^{13}C $\leq$ −18.5, and MS and DBD values increase above the tephra. A second tephra layer, from the Katla volcanic system, was deposited in the lake during the 10th century. The DBD increases above the tephra layers and is >0.24 g cm^{-3} for the remainder of the record. The MS increases continuously towards the top of the record, indicating increased importance of minerogenic material deposition in the sediments. As TN and TC decrease, the δ^{15}N stable isotope ratio begins to increase and is >0‰ c. 1000 cal yr BP and >0.4‰ c. 700 cal yr BP, increasing upwards (Fig. 8). A possible explanation for the higher values of δ^{15}N stable isotope ratios may be decreased algae productivity in response to decreased availability of dissolved nitrogen in the lake (Meyers and Lallier-Vergès, 1999). Another reason may be increased soil organic matter deposition in the lake. Most measurements of δ^{15}N stable isotope ratios in Iceland reveal negative values for both terrestrial and aquatic vegetation (Florian, 2016; Wang and Wooller, 2006); however, positive values are often measured in soils (Florian, 2016) (Fig. 9). The increased δ^{15}N values may therefore be the result of increased input of soil into the lake after *landnám*. The changes in δ^{15}N ratios are accompanied by a drop in δ^{13}C stable isotope ratios to lower values, which indicates a change in the source of the organic material deposited in the lake. On average the δ^{13}C stable isotope ratios of soils and terrestrial vegetation in Iceland are lower than those of algae and aquatic vegetation (Florian, 2016). Therefore, it is likely that after *landnám* more terrestrial material was deposited in the lake, probably reflecting soil erosion. Pollen and spores stored in soil are less well preserved than those preserved in lake sediments, and therefore an increase in deteriorated pollen grains may indicate deposition of reworked material (Havinga, 1967, 1971). Slight increases in deteriorated *Betula* pollen are observed c. 900 cal yr BP and in Poaceae pollen c. 700 cal yr BP (Fig. 11). Furthermore, after c. 1000 cal yr BP (Figs. 4 and 5) there is some increase in Pteridopsida monolete indet. (fern spores), which are resistant to deterioration (Gathorne-Hardy et al., 2009; Havinga, 1967, 1971; Lawson et al., 2007; Schofield et al., 2007), contrary to the expected pattern, as ferns are sensitive to grazing (Kristinsson et al., 2018). This needs to be taken into consideration when interpreting the pollen data. The general trend in the post-*landnám* part of the Galtaból pollen record suggests that the pollen assemblage represents, for the most part, changes in the vegetation community around the lake. However, the possible influence of reworked pollen, for example representing the mid-Holocene woodland phase in the highland (Eddudóttir et al., 2016) cannot be excluded, and this may mute the changes in the pollen assemblage at and after *landnám*.

The C/N ratio in the core is relatively low ~9−12 throughout the record, indicating that algae make up a relatively large part of the organic matter (Meyers, 1997). A trend of decreasing C/N ratio values occurs between 2800 and 800 cal yr BP and only a slight increase is seen c. 800 cal yr BP (AD 1150) (Fig. 8). An increase in C/N ratios is used as one of the main proxies for increased soil erosion in Icelandic lake studies (Geirsdóttir et al., 2009; Harning et al., 2016, 2018; Larsen et al., 2011, 2012). The muted increase in C/N ratios after *landnám*, when an increase in terrestrial input could be expected in the record at Galtaból is therefore surprising. Records of the impacts of land use on lake sedimentation show contrasting effects on C/N ratios of sediments (Enters et al., 2006; Kaushal and Binford, 1999). A possible explanation may be changes in the C/N ratio during diagenesis (Meyers et al., 1984) or alternatively a different response of the relatively organic sediments in Galtaból to soil input compared to other, less organic lake sediments previously studied (Geirsdóttir et al., 2009; Harning et al., 2016, 2018; Larsen et al., 2011, 2012). This demonstrates the difficulties and limitations of using C/N ratios as indicators of soil erosion.

An increase in soil erosion at Galtaból following *landnám* occurred during the Medieval Climate Optimum (MCO), a period of relative warmth in Iceland (Eiríksson et al., 2000; Larsen et al., 2012; Ogilvie and Jónsson, 2001). This suggests that the introduction of land use caused the landscape to pass a tipping point to a state of increased instability (Gísladóttir et al., 2010). Records of storminess measured by the concentration of potassium in the GISP2 ice core (Mayewski et al., 1997) and IP$_{25}$ biomarker inferred drift ice north of Iceland (Cabedo-Sanz et al., 2016) suggest that climate was relatively stable during the first centuries after *landnám*. The MS, δ^{15}N stable isotope records and deteriorated pollen grains from Galtaból suggest that environmental instability began to increase before drift ice and storminess increased (Fig. 11). In the pre-*landnám* environment it is unlikely that periods of cold climate alone would cause large-scale soil erosion in a landscape with a continuous vegetation cover and relatively tall vegetation, such as woodlands. This is demonstrated in a lake sediment record from Kagaðarhóll in the lowlands north of Galtaból, where landscape stability was not undermined under a period of cold climate c. 8800-8100 cal yr BP (Eddudóttir et al., 2018). However, after land use was introduced to the Icelandic environment, soil erosion increased as the climate cooled during the LIA (Streeter and Dugmore, 2014). Woodcutting played an important role in lowland areas, and this may have been the case at higher altitudes as well. Woodcutting would have cleared land for grazing and regeneration of woodland/shrubland may have been prevented due to grazing. Transition from an open birch woodland to heathland with localized erosion and subsequently degraded areas as suggested by the Galtaból record could have been achieved through the introduction of livestock, with subsequent damage to vegetation cover through grazing and trampling (Barrio et al., 2018). This in turn can increase the sensitivity of easily erodible Andosols to freeze-thaw processes and other disturbances (Arnalds, 2015). Once thresholds of environmental states are passed in a sensitive volcanic environment such as Iceland (i.e. disruption of vegetation cover exposing bare ground), it is difficult to re-establish the previous state of environmental conditions (Barrio et al., 2018; Gísladóttir, 2001).

Studies of landscape instability in lowland and coastal areas in Northwest Iceland show evidence that instability occured later there than in the highland, beginning in the period following the deposition of the Hekla 1104 tephra (Riddell et al., 2018b; Tinganelli et al., 2018). The emphasis on dairy in the early Icelandic agriculture (e.g. McGovern et al., 2007) would suggest that livestock were, by

and large, kept near farms. Consequently, the apparent prompt response to land use in the highland becomes enigmatic. Historical sources are silent on the finer details of livestock management, such as how highland environs were used. As a result, we can only assume that even the small part of the livestock that could be grazed remotely, e.g. lambs, castrated rams and bulls, and non-lactating cows and ewes (cf. Thórhallsdóttir et al., 2013) was beyond what the marginal highland ecosystem could support. This may suggest that woodcutting was also an important factor in facilitating environmental changes in the highland. The lowlands, where the climate is milder and primary production is greater, had more capacity to support land use. In many places, this capacity was eventually also crossed (e.g. Lawson et al., 2007; Gísladóttir et al., 2010; Tinganelli et al., 2018). This is in accordance with studies from South Iceland, where soil erosion begins earlier in upland areas before impacting lowland areas (Dugmore and Buckland, 1991; Dugmore et al., 2009). However, the environmental impact of *landnám* is characterised by spatial complexity (Streeter et al., 2015), with a strong settlement signal in some areas (Hallsdóttir, 1987) and a more muted impact in others (Erlendsson, 2007; Erlendsson and Edwards, 2009; Riddell et al., 2018b; Roy et al., 2018; Tisdall et al., 2018).

5.3. Soil erosion after the landnám period

An increase in drift ice north of Iceland and increased storminess over Greenland is seen in records from c. 600 cal yr BP (AD 1350) (Fig. 11; Cabedo-Sanz et al., 2016; Mayewski et al., 1997). This is in good agreement with varve records from Hvítárvatn, south of Galtaból, where varve thickness increases after the mid-13th century (Larsen et al., 2011). There are however no clear indications of this change seen in the Galtaból sedimentary proxies or pollen (Figs. 8 and 11). The lack of response from the sedimentary proxies at the onset of the Little Ice Age suggests that colder climate was not the dominant factor influencing soil erosion in the centuries after *landnám*. A shift in sediment properties occurs c. 330 cal yr BP (AD 1620), with a decrease in TC to <4.7% and TN to <0.48%. A further shift to lower $\delta^{13}C$ ratios (<−19‰) occurs c. 250 cal yr BP (AD 1700). This is accompanied by an increase in minerogenic material deposited in the lake, observed from the DBD and MS, as $\delta^{15}N$ stable isotope ratios continue to increase upwards. This may indicate an intensification of soil erosion in response to changes in land use and/or a colder climate during the LIA. Disentangling the causes of increased soil erosion in the 17th century is however difficult, but it is likely that changes in land use influenced the way climate impacted the environment. A similar increase in soil erosion is seen in South Iceland at the end of the 16th century linked to cold climate and increased storm frequency during the LIA (Streeter and Dugmore, 2014; Streeter et al., 2012).

5.4. Implications of soil erosion for paleoenvironmental reconstructions

Soil erosion implies that older organic matter previously stored in soil becomes mobile and is redistributed. Older OM eventually arrives in lakes and other archives. This carries with it the implication that after *landnám*, some of the pollen, carbon and nitrogen, as well as minerogenic material in the sedimentary archive may be reworked from soil. Dating of a *Betula nana* leaf at 134.5 cm depth in the Galtaból core yielded a date that was too old compared to the tephrochronology of the core and may be further indication of reworking of older carbon (Fig. 3 and Table 3). The same trend is seen in the lake core from nearby Barðalækjartjörn (Eddudóttir et al., 2016). This has been observed in other paleological studies

from Iceland (e.g. Gathorne-Hardy et al., 2009). The increase in deteriorated *Betula* and Poaceae pollen and fern spores (Figs. 4, 5 and 11) and total Pteridophyte spores (Fig. 11) after c. 1000 cal yr BP suggests an increase in the deposition of reworked terrestrial material (Havinga, 1967, 1971). An extensive system of soil escarpments is located to the southeast of the lake, as well as to the north of the lake and east of the river Blanda (Fig. 2). These may provide source areas for reworked organic material, including pollen and spores. Evidence of soil erosion is found in most dryland soil profiles in the region near Galtaból, however a tephra from a Hekla eruption in AD 1693 (257 cal yr BP) is preserved in both lowland and highland profiles. Other tephra markers, such as Hekla 1104 (AD 1104), Hekla 3 and Hekla 4 are absent from many profiles, suggesting removal by soil erosion or the absence of vegetation cover to trap the tephra prior to AD 1693 (Guðbergsson, 1996). Records of landslides spoiling hayfields in the early 18th century suggest that decreased vegetation cover and exposed soils may have increased incidents of mass movement of soil and gravel in the region (Magnússon and Vídalín, 1926). This underscores the challenges involved in using post-*landnám* records for interpretations of paleoenvironmental and paleoclimate data.

5.5. Considerations for the current state of the Icelandic highland

Examinations of past human impacts on the environment aid understanding of long-term relationships between land use and ecological processes. This improves the basis for informed decisions on ecological restoration and future management of grazing areas. The Galtaból record clearly shows the shift that the highland environment underwent at *landnám* with the introduction of land use. Importantly, the response of the ecosystem to tephra fall and cold climate, that is reflected in the record in earlier periods was changed as humans began to utilise highland resources.

The current highland environment is in large part a human-made construction, where natural ecosystems have been transformed to unstable ecosystems, maintained by human activities; some continue to degrade. The contemporary state of the Icelandic environment has local, regional and global implications. On a local scale, the current surface of much of Iceland is unfit to capture tephra fall from even small eruptions (Arnalds et al., 2013). This leads to questions about the aftermath of potential large explosive eruptions in the future. Due to large, sparsely vegetated areas, sandstorms and poor air quality are very likely to become long-term problems in parts of Iceland following such an eruption (Arnalds et al., 2013). On a regional scale, Iceland is a significant dust source (Arnalds et al., 2016; Blechschmidt et al., 2012; Ovadnevaite et al., 2009) and is the largest dust source in the sub-Arctic and Arctic (Dagsson-Waldhauserova et al., 2014). Although much of the dust released to the atmosphere originates from glacier forefields and floodplains, the current state of vegetation plays a role. On a global scale, soils accumulated over millennia in Iceland have changed from carbon sinks into sources of atmospheric C due to past and ongoing erosion (Óskarsson et al., 2004). Reclamation of lost natural ecosystems in Iceland should therefore be considered a priority for nature conservation, carbon emissions and preparedness for future volcanic eruptions in Iceland. Paleoenvironmental reconstructions such as this one can provide baselines for restoration and reclamation of degraded areas. Knowledge of the Icelandic Holocene environment can help create more focused land restoration goals in the future. Paleoenvironmental records provide information of environmental conditions under different climate regimes and land use scenarios, as well as responses to volcanic eruptions of varying sizes. By using paleoenvironmental records from the highland to provide baselines for restoration and land

reclamation it may be possible to provide a guide for sustainable land use of the highland, building on the information gathered and avoiding the mistakes made in the past. For this, more research in the highland is needed.

6. Conclusions

The Galtaból lake sediment record demonstrates the large impact that *landnám* had on the Icelandic highland environment. While the pre-*landnám* environment was able to recover from the impacts of tephra fall and a cooling climate, a shift to a state of greater disturbance is seen at the time of *landnám*. The decrease in pollen of palatable plant species (preferred by grazing animals) after c. 1000 cal yr BP (AD 950) and the increase in spores of coprophilous fungi c. 800 cal yr BP (AD 1150) suggests that Auðkúluheiði was used as a grazing area after the settlement. Despite a relatively warm climate during the MCO, the introduction of land use caused a change in the vegetation communities near the lake, increased soil erosion and an ecosystem shift to a degraded state. Although the beginning of the LIA is not reflected by increased soil erosion in the Galtaból record, this feature is observed from the early 17th century, indicated by increased minerogenic material deposited in the lake and a higher $\delta^{15}N$ stable isotope ratio. The combination of cooling climate and increased emphasis on sheep farming are likely to have caused increased soil erosion, and land use impacts made the environment more susceptible to the effects of colder climate. Due to the extensive erosion and reworking of soil in Iceland after *landnám*, care needs to be taken when interpreting post-*landnám* data for environmental and climate proxies. The Galtaból record serves as a reminder of the large-scale changes humans can cause in a landscape without careful management of natural resources.

Author statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.quascirev.2020.106363.

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