

# Late survival of woodland contrasts with rapid limnological changes following settlement at Kalmanstjörn, Mývatnssveit, northeast Iceland

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The settlement of Iceland is known to have had profound impacts on vegetation and landscape stability, but there remain uncertainties around the spatial variability and timing of environmental change, and the impacts of settlement on aquatic ecosystems. Here a new multiproxy palaeoenvironmental reconstruction spanning the last 3000 years is presented from Kalmanstjörn, a small lake in Mývatnssveit, northeast Iceland. Sedimentology, pollen and non-pollen palynomorphs, and geochemical proxies, dated using tephrochronology, are used to reconstruct terrestrial vegetation, landscape stability and aquatic ecosystems. The data reveal complex environmental dynamics after settlement. At this site, substantial tree populations persisted until the late 15th century, in strong contrast to the rapid deforestation shown by almost all other records from Iceland. The eventual loss of woodland may have been caused by changes in direct human activity and the location of extensive grazing, in combination with Little Ice Age climatic cooling. The loss of woodland was accompanied by increased soil erosion. Conversely, the lake ecosystem showed an immediate response to settlement, becoming more productive for several centuries, perhaps in response to increased availability of nutrients from grazing herbivores. The late persistence of woodland in the Kalmanstjörn record adds to our understanding of the spatial variations in ecosystem responses to settlement in Iceland, while the evidence for decoupling of the aquatic and terrestrial systems suggests that palaeolimnological reconstructions focusing on aquatic ecosystem responses may be important new sources of information on the wider ecological consequences of human settlement.

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The environment of Iceland has undergone significant changes since the colonization of the island by Norse settlers in the 9th century AD. Today, woodland covers just 1% of the island and 96% of soils are experiencing erosion (Arnalds 1987), but palaeoenvironmental reconstructions have revealed that before settlement woodland cover was much higher and erosion far less extensive (Ólafsdóttir *et al.* 2001; Ólafsdóttir & Guðmundsson 2002; Streeter 2011; Streeter *et al.* 2015). The first widespread settlement of Iceland, known as *Landnám* (Old Norse for 'land taking'), occurred around AD 877 (McGovern *et al.* 2007; Schmid *et al.* 2017). Before settlement, changes in the Icelandic ecosystem appear to have been driven primarily by climatic change and, in this volcanic landscape, by the (often short-lived) ecological consequences of tephra deposition events (Eddudóttir *et al.* 2015, 2016). Settlement saw the introduction of new anthropogenic pressures, including grazing by mammals, woodland clearance, and burning, which caused widespread ecological change (Dugmore *et al.* 2005; McGovern *et al.* 2007; Streeter *et al.* 2015). These new pressures were imposed upon a system that continued to respond to climatic changes, the most important being the transition between the Medieval Warm Period (MWP; *c.* AD 780–1250) and the Little Ice Age (LIA; *c.* AD 1250–1900; Ogilvie *et al.* 2000; Geirsdóttir *et al.* 2009). Tephra deposition also continued to play a role in environmental change: not only did

it continue to directly impact ecosystems as it was deposited, but it also changed the intensity and distribution of grazing pressures as farmers moved to protect their livestock (Wilcox 1959; Edwards *et al.* 2004). Understanding the relative contributions of each of these drivers (climate, volcanism, and anthropogenic activity) to environmental change is a major challenge for palaeoenvironmental research in Iceland.

Our current understanding suggests that the impacts of the settlement of Iceland on terrestrial vegetation were widespread but also spatially variable (Streeter *et al.* 2015). The majority of palaeoenvironmental reconstructions have suggested that, where woodland was widespread before settlement, it substantially decreased in extent within decades of *Landnám* (Þórarinnsson 1944; Einarsson 1961, 1963; Hallsdóttir 1987, 1995; Riddell *et al.* 2018b). The majority of records showing rapid deforestation come from either mire sites, which produce pollen records from which local conditions (rather than large-scale regional trends) can be most easily reconstructed (Bunting *et al.* 2004), or from sites close to early farms, where early and rapid clearance would be expected. However, some lake sediment sequences (which should reflect a larger pollen source area), for example from Vatnskotsvatn and Helgutjörn, show similarly rapid responses (Hallsdóttir 1995; Jónsson 2009), suggesting that rapid deforestation is not necessarily an artefact of a local pollen signal and that at least

some areas did lose woodland cover rapidly on a catchment scale. Over the last 15 years, this narrative has been challenged by new records that show persistence of woodland for several centuries after settlement. For example, the record from Breiðavatn, a lake in western Iceland, shows only a slight initial decrease in woodland extent immediately after *Landnám*, with large-scale deforestation occurring around AD 1300 (Gathorne-Hardy *et al.* 2009). In the Mývatnssveit region in northeast Iceland, a cluster of records similarly indicates that woodland survived for many centuries before deforestation to approximately present-day levels (small patches still persist today): the Helluvaðstjörn lake record shows only a slight decrease in *Betula pubescens* abundance immediately after *Landnám*, with a final reduction only after AD 1300 (Lawson *et al.* 2007); a nearby peat record from the Grænavatn estate similarly shows a small reduction in woodland extent at *Landnám* with a second, final decline after AD 1300 (Colquhoun *et al.* 2010); and a peat record from the Hofstaðir farm estate suggests that low-density woodland was preserved as late as AD 1790 before it was cleared, although the record probably reflects the vegetation of only a small area (Tisdall *et al.* 2018). Yet with only one regional-scale record (from Helluvaðstjörn), it remains unclear for how long widespread woodland cover persisted throughout Mývatnssveit and whether there was significant spatial variability in environmental changes – a knowledge gap that this paper aims to address.

The impact of settlement on Iceland's freshwater aquatic ecosystems is perhaps even more poorly understood. Lake ecosystems may prove to be more sensitive to settlement and subsequent disturbances than may be inferred from terrestrial pollen data alone; for example, small-scale changes in land use (such as limited woodland clearance) may be obscured within the pollen spectra but may have a large impact on the inputs of material into a lake (Paus 2013; Stivrins *et al.* 2019). Therefore, the incorporation of information from the lake ecosystem can complement data obtained about terrestrial environments by providing insights into landscape dynamics on a well-defined catchment scale, particularly in small sub-arctic lakes, which are likely to be sensitive to changes in inputs (Dubois *et al.* 2018). Across the world, the response of aquatic systems to anthropogenic activity is typically characterized by eutrophication, often driven by the mobilization of soil nutrients into lakes and rivers after deforestation (e.g. Leahy *et al.* 2005; Meyers 2006; Mills *et al.* 2017). In Iceland, most studies using palaeolimnological proxies such as chironomids have focused on palaeoclimatic reconstructions and have thus been intentionally located far from centres of human activity (Axford *et al.* 2009; Holmes *et al.* 2016). Only two records exist that combine high-resolution palynological and palaeolimnological data through the settlement period: Helluvaðstjörn and Breiðavatn, both of which show only a small change in woodland extent at

*Landnám* (Lawson *et al.* 2007; Gathorne-Hardy *et al.* 2009). At Helluvaðstjörn, *Landnám* is marked by increased concentrations of chironomid head capsules and by increased accumulation rates of aquatic pollen and spores and *Pediastrum* colonies; this suggests that nutrient availability increased immediately after *Landnám* (Lawson *et al.* 2007). At Breiðavatn, *Pediastrum* abundance greatly increased after *Landnám*, again indicating a change in nutrient availability. The current paucity of data for aquatic ecosystems and for soil dynamics after settlement makes it difficult to reconstruct the nature and the causes of aquatic system dynamics in Iceland, and their causal relationships with terrestrial vegetation.

This study presents a new palaeoenvironmental data set from Kalmanstjörn, a lake in the Mývatnssveit area, northeast Iceland. Mývatnssveit is one of the most important areas in Iceland for understanding the dynamics of *Landnám*, as it has been extensively excavated and data from the region have been used to inform interpretations of settlement processes across Iceland (see below; Vésteinsson & McGovern 2012). However, the region still lacks palaeoenvironmental data on a similar scale to the archaeological data set. This hinders the development of models of landscape change that are able to sufficiently account for the spatial variability that might be expected. At present, only one lake record (Helluvaðstjörn) is available for understanding regional-scale environmental responses to settlement in the region (Fig. 1B; Lawson *et al.* 2007), but in order to improve our knowledge of the impacts of settlement dynamics on ecosystems more regional-scale lake records are required. This study uses sedimentology, organic geochemistry and palaeoecological data from a sediment record obtained from Kalmanstjörn, a lake in the northwest of Mývatnssveit, to reconstruct terrestrial vegetation, landscape stability, and aquatic ecosystem developments from 950 BC (approximately the time of deposition of the Hekla 3 tephra layer) to the 19th century AD. In doing so, this study aims to: (i) further develop the terrestrial palaeoenvironmental history of Iceland and the Mývatnssveit region, (ii) investigate the evolution of the aquatic ecosystem through the settlement period, and (iii) investigate the causal relationships between environmental systems in response to human activity, climate change, and tephra deposition.

## Study area

Mývatnssveit is an inland area centred on Lake Mývatn, the third-largest freshwater lake in Iceland. The climate of Mývatnssveit is more continental than other areas of Iceland, with an average annual temperature range of 13–15 °C, and it is among the driest areas, with average annual precipitation of 400 mm a<sup>-1</sup> (Einarsson 1979). Lakes are covered by ice for much of the year; Lake Mývatn experiences an average of *c.* 190 days of ice

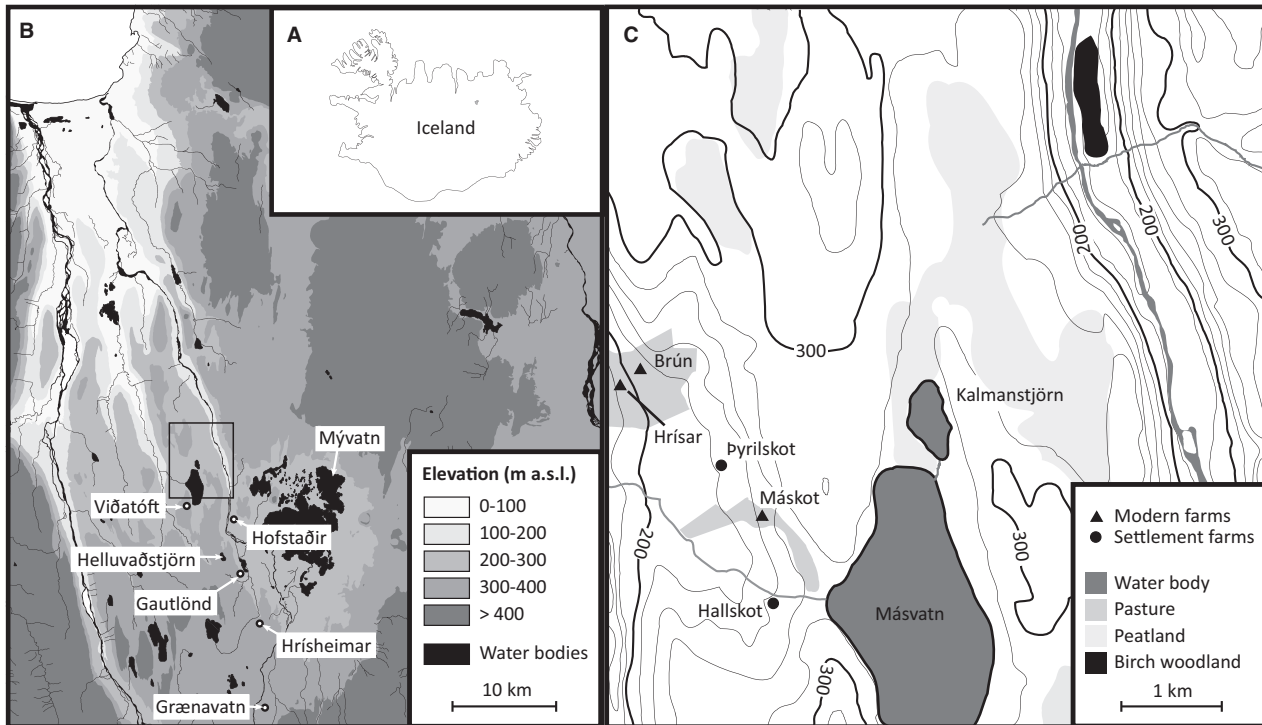


Fig. 1. Map of Iceland (A), the Mývatnssveit region with key sites mentioned in the text labelled (B), and the local environment around Kalmanstjörn (C). Elevation data from National Land Survey of Iceland (2016). Land-use data from the CORINE land cover map 2012 (European Union 2012). The black box in (B) marks the area shown in (C).

cover per year (Rist 1979). The vegetation of Mývatnssveit is presently dominated by dwarf-shrub (*Betula nana*, *Empetrum nigrum* and *Salix*) and mire (Poaceae and Cyperaceae) communities in the rangelands, and mountain birch (*B. pubescens* ssp. *tortuosa*) is present in small populations where it is protected from grazing, such as on rough lava fields (Lawson *et al.* 2009).

Mývatnssveit has one of the densest concentrations of excavated archaeological sites in the Norse North Atlantic region (McGovern *et al.* 2007; Vésteinsson & McGovern 2012). Lake Mývatn is a relative hotspot of biological diversity, and lake resources may have provided settlers with the opportunity to supplement their pastoral subsistence strategy with fishing and egg-collecting while the earliest farms were being established and increasing in productivity (although there is little evidence that any farm adopted fishing as the dominant part of its resource strategy; Vésteinsson & McGovern 2012). Archaeological data suggest that all good-quality land was probably occupied by AD 950 (Vésteinsson & McGovern 2012). A series of abandoned farms in the colder, drier highlands to the south of Mývatn are thought to have been established in a second wave of settlement and survived only until the 12th century; these settlements appear to have been unsustainable in the long-term, in part due to environmental pressures such as soil erosion and climatic change in these

marginal settings and in part due to societal pressures (Vésteinsson *et al.* 2014). There is evidence across the region for charcoal production to facilitate metallurgy until the 12th century, which would require the (probably intentional) preservation of woodland populations far in excess of current *B. pubescens* stands to supply sufficient wood (McGovern *et al.* 2007).

Kalmanstjörn (latitude 65°39.46'N, longitude 17°14.03'W; Fig. 1C) is a small (~0.27 km<sup>2</sup>) and shallow (maximum depth <2 m) lake situated 265 m above sea level. The lake probably occupies a glacially scoured depression. The lake catchment is gently sloped and is characterized by andesitic soils overlying glacial till, with abundant small-scale (<1 m), low-relief, frost-heave hummocks (*thúfur*). Heathland species, dominated by *Empetrum nigrum*, characterize the drier hummocks while members of the Cyperaceae family populate the hollows. Kalmanstjörn is situated on a narrow (~6 km wide) ridge between two river valleys (Laxádalur and Reykjadalur) and sits close to the watershed separating the two valleys, and to the south of Kalmanstjörn is the much larger Lake Mávratn (Fig. 1C). As a result, Kalmanstjörn has a relatively small catchment and may be expected to be disproportionately dominated by aeolian rather than hydrological inputs. As a small lake, Kalmanstjörn probably recruits local pollen from no further than 1–2.5 km from the lake (based on estimates from slightly smaller lakes in

southern Scandinavia; Nielsen & Sugita 2005; Hellman *et al.* 2009; Hjelle & Sugita 2012). The upper end of this range suggests that the local Kalmanstjörn signal will broadly reflect the vegetation dynamics of the ridge on which Kalmanstjörn lies, while the remainder of the assemblage (potentially over 50% of the pollen signal; Nielsen & Sugita 2005) will be representative of the vegetation of the wider region.

Today, three farms are operational within 3 km of the lake: Máskot (occupied from at least the 16th century; Vésteinsson 2011), Hrísar and Brún (Fig. 1C). Archaeological evidence indicates that the local landscape on the edge of the ridge has been occupied since shortly after *Landnám*. Þyrilskot (Fig. 1C), which was probably never fully established as a farm, preserves evidence for soil improvement prior to AD 940, with a small enclosure built after AD 940 (Vésteinsson & McGovern 2012). Viðatóft, on the southwest corner of Mávötn (Fig. 1B), comprises two concentric enclosures, the innermost of which currently encloses a wet bog; the enclosures may represent attempts to protect an early area of intensive productivity in the inner enclosure and a later, more expansive, area of cultivation when the attempts at intensive cultivation proved unproductive (Vésteinsson 2011). The Hallskot farm (Fig. 1C) was also established prior to AD 1158 and consists of an enclosure and a number of structures, including what may be a byre (Vésteinsson 2011; Vésteinsson & McGovern 2012). Additionally, a number of sites that are undated but likely represent the Viking Age have been identified in both the Laxárdalur and Reykjadalur valleys (Vésteinsson & McGovern 2012). Wall structures pre-dating the 12th century are prevalent in the two valleys, representing the delineation between exclusive farmland and the communal rangelands (Einarsson 2015). Across the region there is evidence for abandonment of farms around the 12th century, reflecting a social restructuring, which involved a concentration of households onto a smaller number of farms; this is likely to have affected the land use of outfields, but little palaeoenvironmental evidence is currently available for the impacts that this had on ecosystems (Vésteinsson 2011). There was, therefore, probably a consistent local land use for the first three centuries of the settlement period, possibly followed by a change in land use from the 13th century onwards. The modern and archaeological evidence suggest that the Kalmanstjörn catchment has remained on the margins of areas of more intensive land management since settlement.

## Material and methods

### *Sampling and sedimentology*

A 290-cm sediment core was obtained from the centre of Kalmanstjörn using a Russian corer with a 50-cm chamber. Core segments were obtained with a 10-cm

overlap, and segments were correlated using stratigraphical information (e.g. tephra layers) and magnetic susceptibility measurements (see below). The core was stored at 4 °C until analysis. The sediment composition was described using the Troels-Smith method (Troels-Smith 1955). The uppermost 10 cm of the core was not subsampled for analysis as the integrity of the sediment in this section was poor. Volumetric magnetic susceptibility was measured on 1-cm<sup>3</sup> subsamples at 2-cm intervals using a Bartington Instruments MS2 meter and a Bartington MS2G probe. 1-cm<sup>3</sup> subsamples were taken at 2-cm intervals for loss-on-ignition analysis; the subsamples were dried at 105 °C for at least 12 h for dry bulk density determination and ignited at 550 °C for 4 h for organic matter determination (Heiri *et al.* 2001; Santisteban *et al.* 2004).

### *Geochemical analysis*

Samples for geochemical analyses were taken at depths that correspond with samples taken for pollen analysis (see below). Samples were oven-dried at 40 °C, then crushed into a fine powder and homogenized using a pestle and mortar (Nieuwenhuize *et al.* 1994). 20 mg of material was weighed into a capsule and acidified with 10% HCl to remove inorganic carbon. Samples were analysed using an Elementar vario EL cube CHNS Elemental Analyser using sulfanilamide as a standard. The atomic carbon and nitrogen concentrations were used for calculation of the C:N ratio.

### *Pollen, spore and Pediastrum analysis*

Samples for pollen analysis were taken at 8-cm intervals, increasing to 4-cm intervals above the *Landnám* tephra layer and 2-cm intervals around tephra layers and around periods of palaeoecological change. Pollen preparation followed standard procedures using a density separation technique (Nakagawa *et al.* 1998; Campbell *et al.* 2016), as follows. 1-cm<sup>3</sup> subsamples were spiked with *Lycopodium clavatum* tablets to allow estimates of concentration (Stockmarr 1971). Samples were treated with 10% HCl and 10% KOH, then sieved to remove material >180 µm. Lithium heteropolytungstate (tradename LST Fastfloat) at a density of 1.88 g cm<sup>-3</sup> was used for density separation. Samples then underwent acetolysis, then dehydration using tert-butanol. Samples were stored and mounted in silicone oil.

Pollen and non-pollen palynomorphs were identified at 400× magnification (with critical examination where required at 1000× magnification) until at least 300 terrestrial pollen grains had been counted (cf. Maher 1972). Some Icelandic studies exclude Cyperaceae from the pollen sum where it dominates an assemblage to avoid over-representation of a local signal (e.g. Gísladóttir *et al.* 2010; Riddell *et al.* 2018a). However, because Kalmanstjörn has an area of ~0.27 km<sup>2</sup> and

the core was taken from the centre of the lake (approximately 200 m from the nearest shore) the Kalmanstjörn record was not expected to be (and did not appear to be) disproportionately affected by local Cyperaceae populations around the margin of the lake, and Cyperaceae was, therefore, included in the pollen sum. Pollen identification followed Moore *et al.* (1991) and the pollen reference collection held at the University of St Andrews, and taxonomy and nomenclature follows Lawson *et al.* (2007). *Betula pubescens* and *B. nana* produce morphologically similar pollen. Typically the grains of *B. pubescens* are larger than those of *B. nana*, although hybridization between the two species can produce intermediate grain sizes and there is often an overlap in the size distributions (Karlsdóttir *et al.* 2007). Nevertheless, separation of the two species using grain diameter can be used to generate an estimate of the proportion of *B. pubescens* and *B. nana* grains in a sample. A number of separation thresholds have been proposed, but here we follow earlier separation criteria: *Betula* grains were measured at 1000× magnification, and those <20.5 µm in diameter were assigned to *B. nana* while all others were assigned to *B. pubescens* (Mäkelä 1996; Caseldine 2001). Each grain assigned to *B. pubescens* was assessed for evidence of damage and recorded in four categories: corroded, degraded, folded/crumpled, and broken (Elsik 1966; Cushing 1967; Havinga 1967). Pollen data were zoned based on terrestrial pollen using the binary splitting sum-of-squares method in Psimpoll (Bennett 2009). The record was separated into two statistically significant zones that are divided at *c.* AD 1480. To aid the following description and interpretation of the data, the earliest zone is separated into two subzones representing the pre-settlement (KMN-1a) and post-settlement (KMN-1b) periods, separated by the *Landnám* tephra layer (see below for identification and correlation).

Identification of coprophilous fungal spores followed Feeser & O'Connell (2009) and Cugny *et al.* (2010). *Pediastrum* colonies were counted where more than half of the colony was intact, and identification followed Jankovská & Komárek (1995, 2000) and Komárek & Jankovská (2001). Proportions of terrestrial spores, aquatic pollen and spores, fungal spores and *Pediastrum* colonies were calculated using the sums of the terrestrial pollen plus all taxa in the relevant group. Microscopic charcoal fragments >10 µm were identified but abundances were consistently low with no discernible patterns, and data are, therefore, not presented here.

#### *Tephra geochemistry and age model*

Tephra layers were selected for geochemical analysis based on their stratigraphical integrity, thickness and

discreteness, focusing on parts of the stratigraphy where important changes in the proxies occurred. In total, eight layers were selected for analysis (Fig. 2; Table S1), while two additional layers were excluded as they were diffuse and are, therefore, unlikely to represent primary tephra deposition. Tephra shards were isolated from the sediment matrix using standard acid digestion procedures whereby samples were treated with hot concentrated H<sub>2</sub>SO<sub>4</sub> and HNO<sub>3</sub> (Dugmore *et al.* 1992). Shards were mounted in an epoxy resin (tradename EpoThin2), ground to expose shard surfaces, polished, and carbon coated (Hall & Hayward 2014). Tephra samples were analysed using a Cameca SX100 electron microprobe at the University of Edinburgh for the determination of major elemental oxides. Analysis used an accelerating voltage of 15 kV, a current of 2 nA/80 nA, and a beam diameter of 8 µm in order to avoid the mobilization of Na, and subsequent overestimation of Al and Si and underestimation of Na and K (Hayward 2012). Analytical accuracy and precision were determined using measurements of a rhyolitic (Lipari) and basaltic (BCR2g) standard at the beginning of a set of analyses and then every 24 h thereafter (Table S2).

Correlation of tephra layers was based on comparison with published geochemical data (Tephabase: <http://www.tephrabase.org>; Larsen *et al.* 2002; Gudmundsdóttir *et al.* 2012) and with reference to other records with tephrostratigraphical profiles in the region (Larsen *et al.* 2002; Lawson *et al.* 2007; Adderley *et al.* 2008; Brown *et al.* 2012; Gudmundsdóttir *et al.* 2012; Sigurgeirsson *et al.* 2013; Barclay 2016; Tisdall *et al.* 2018). Six tephra layers in the record have been correlated with independently dated tephra (Fig. 2): Hekla 3 at 152 cm (radiocarbon dated to 2879±34 <sup>14</sup>C a BP; Dugmore *et al.* 1995); the base of the *Landnám* tephra layer (LTL) at 118 cm (dated to AD 877±1; Schmid *et al.* 2017); the base of the V-Sv tephra layer at 106.5 cm (previously referred to as V-950 and now dated to AD 938±6; Schmid *et al.* 2017); the base of a *Veidivötn* layer at 85.5 cm that is geochemically and stratigraphically similar to one found in nearby Lake Mývatn (dated to AD 1159; Sigurgeirsson *et al.* 2013); the base of V-1477 at 44 cm (historical records providing a date of AD 1477); and the base of V-1717 at 27 cm (historical records providing a date of AD 1717). Using these six tephra layers and the year of coring as the age for the top of the core, an age model was constructed using a Bayesian approach in the Bacon package in R version 3.4.0 (Fig. 3; Blaauw & Christen 2011; R Core Team 2017). The Bacon age-depth model normally permits only small variations in sediment accumulation rate across dated horizons in order to best simulate a natural depositional environment, but due to the significant change in accumulation rate observed across the LTL (which has a precedent in the Helluvaðstjörn record; Lawson *et al.* 2007), a boundary was included in the

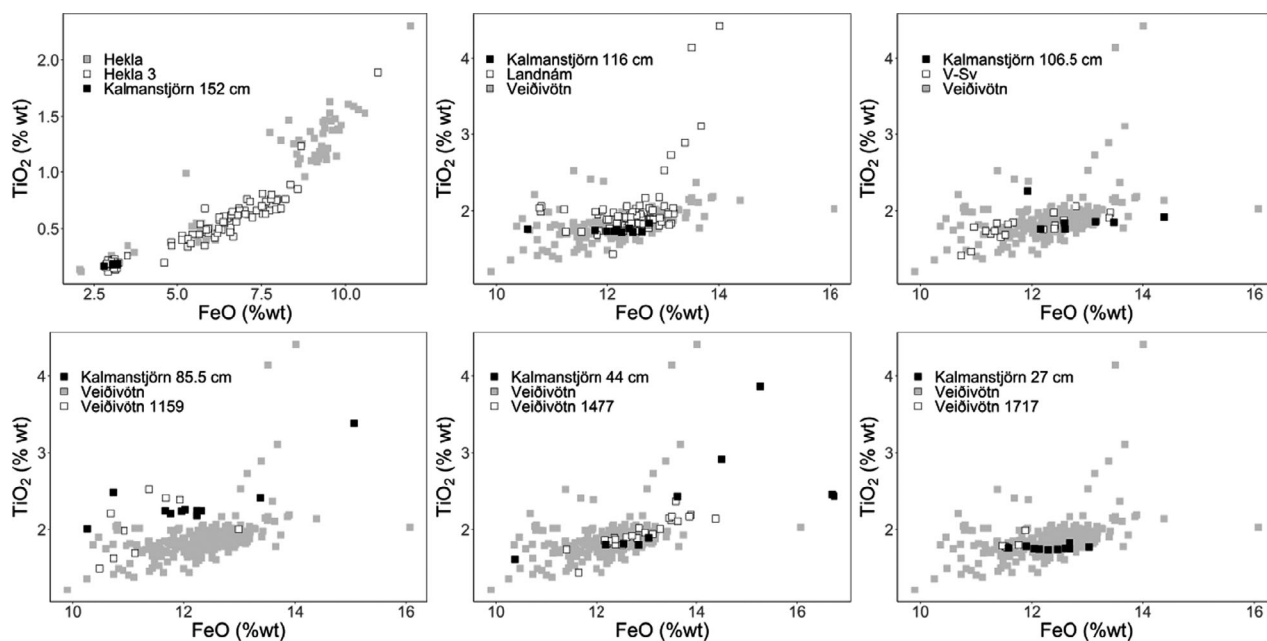


Fig. 2. Geochemical tephra biplots. Data from the Kalmansjörn record are overlain on data for the source volcanic system and the eruption to which the layer has been correlated (data from Hannon *et al.* 1998; Boyle 1999; Larsen *et al.* 1999, 2002; Wastegård *et al.* 2001; Wastegård 2002; Pilcher *et al.* 2005; Lawson *et al.* 2007; Gudmundsdóttir *et al.* 2012; Sigurgeirsson *et al.* 2013; Streeter & Dugmore 2014). Raw data can be found in Table S1.

model at the depth of the LTL to permit a larger change in sediment accumulation rate (Fig. 3).

## Results

### *Sedimentology and organic geochemistry*

Magnetic susceptibility (MS), dry bulk density (DBD) and organic matter (OM) covary through the succession (Fig. 4). Typically, high OM values correspond with low DBD and MS values (and vice versa). OM shows the most inter-sample variability. The most prominent long-term trends include a slow reduction in OM above the Hekla 3 tephra layer and an increase in OM above the LTL. Above the LTL, high OM values are interrupted only where tephra layers are found. The largest response, seen in all sediment properties, is to the V-1477 tephra. Sediment accumulation rates show a marked increase across the LTL horizon, increasing from  $0.02 \pm 0.001 \text{ cm a}^{-1}$  below the LTL to an average of  $0.13 \pm 0.08 \text{ cm a}^{-1}$  above the LTL (Fig. 3).

Trends in total organic carbon (TOC) and total nitrogen (TN) closely follow OM trends: they decline just beneath the LTL, then increase above the LTL with sharp, short-lived decreases coinciding with tephra layers (most prominently the V-1477 tephra layer). C:N ratios through the record are typically  $<15$ , with sharp increases coinciding with tephra layers. Between tephra layers there is some evidence of C:N values gradually increasing (for example between the V-Sv and V-1159

layers, and between the V-1159 and V-1477 layers) before returning to previous values above the upper tephra layer (Fig. 4).

### *Terrestrial pollen and NPPs*

*Zone KMN-1a (850 BC–AD 877).* – Zone KMN-1a represents the pre-settlement period and is characterized by limited variability in the terrestrial pollen assemblages, which are dominated by arboreal pollen (Fig. 5A). The most significant taxa are *B. pubescens* (35–45%), *B. nana* (10%), Poaceae (10%), and Cyperaceae (which increases gradually from 15 to 30% before AD 200 and then shows little variability). The woody shrub taxa (*Salix* and *Juniperus communis*) both remain  $<5\%$  throughout the zone. *Empetrum nigrum* is the dominant Ericaceae species in the zone ( $<2\%$ ). The only other herbaceous taxon of importance is *Thalictrum* (5%).

Terrestrial spores are sparse until AD 650 when *Selaginella selaginoides*, *Lycopodium annotinum* and *Sphagnum* percentages increase (Fig. 5B). Of these *S. selaginoides* is the most abundant, reaching a maximum of 5%. Aquatic pollen and spores are dominated by *Myriophyllum alterniflorum*, which varies between 10 and 30%. Higher values are attained around AD 70 and AD 870. *Isoetes* consistently forms a minor component ( $<2\%$ ) of the aquatic assemblage. The number of *Pediastrum* colonies increases gradually before stabilizing at maximum values after AD 700.



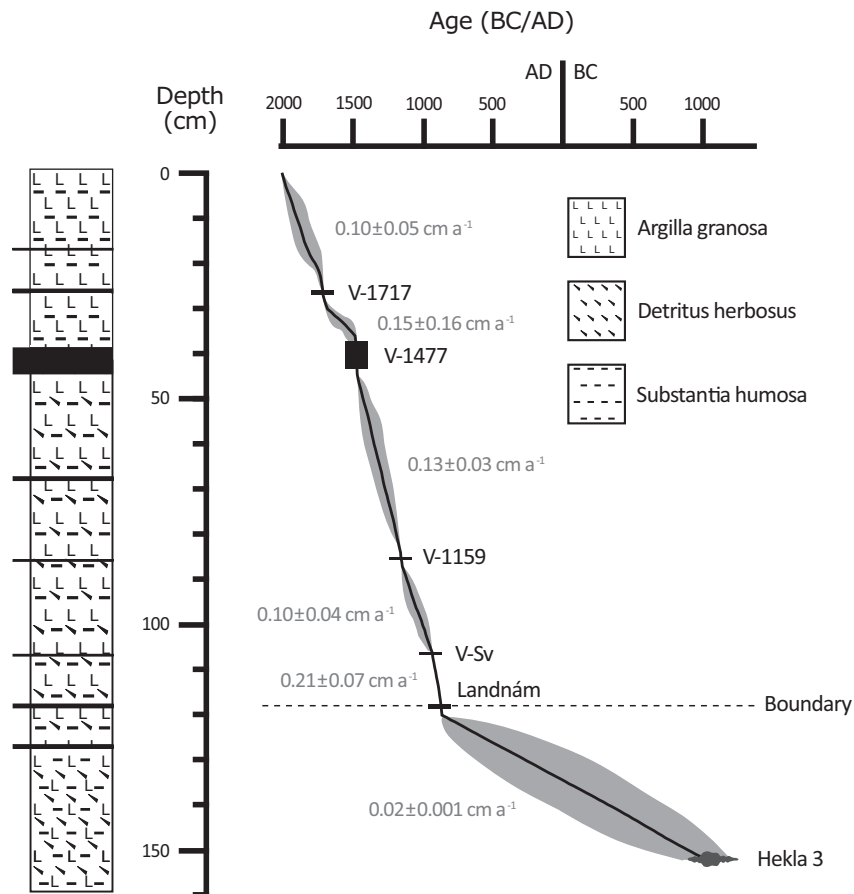


Fig. 3. Stratigraphy and age-depth model for the Kalmanstjörn core. The boundary was included in the age-depth model to allow for the large change in sediment accumulation rate above the *Landnám* tephra layer. Tephra layers are marked by the black lines extending from the stratigraphical log. Average sediment accumulation rates between each dated tephra layer are shown in grey text.

**Zone KMN-1b (AD 877–AD 1477).** – Zone KMN-1b represents the first 600 years following settlement and is, like KMN-1a, characterized by terrestrial pollen assemblages dominated by arboreal pollen that show little variability except in samples around tephra layers (Fig. 5A). *B. pubescens* percentages vary between 35 and 45%, with lower values coinciding with tephra layers. *B. nana* (10–15%, with a large short-lived peak to 20% at AD 1090), Poaceae (7.5–15%) and Cyperaceae (25–35%) are similarly stable, with their highest values occurring when tephra layers are present. The tephra layers that coincide with the largest assemblage changes are the LTL and the V-1159 layers. The woody shrub taxa (*Salix* and *Juniperus communis*) maintain their low percentages from KMN-1a. *J. communis* declines to consistently low (<2%) percentages after AD 1300. Ericaceae remain scarce and decrease to their lowest values in the record after AD 1200. Minor taxa (including *Thalictrum* and members of the Apiaceae and Ranunculaceae families) increase slightly above the LTL.

Terrestrial spores retain their low values from KMN-1a with the exception of AD 1110–1170, when

*S. selaginoides* percentages increase slightly (Fig. 5B). The coprophilous spore types *Sporormiella* and *Sordaria* appear sporadically at low percentages after AD 950. Percentages of aquatic pollen and spores increase. *Isoetes* percentages increase to vary between 2 and 4% immediately above the LTL. *M. alterniflorum* percentages initially decrease until AD 950. They then increase to >30% between AD 1100 and AD 1350, before gradually decreasing through the remainder of the zone (with the exception of a peak to >30% at c. AD 1400). The main *Pediastrum* taxa (*Pediastrum boryanum* undiff., *P. integrum*, and *P. subgranulatum*) that appeared in KMN-1a maintain percentages similar to the previous zone. *P. boryanum* var. *cornutum* becomes a significant part of the assemblage during KMN-1b and exhibits two large (>35%) peaks at AD 1050 and AD 1400 with values >10% between the peaks.

**Zone KMN-2 (AD 1477–AD 1850).** – Zone KMN-2 represents the environment after the V-1477 tephra deposition and is characterized by low proportions of

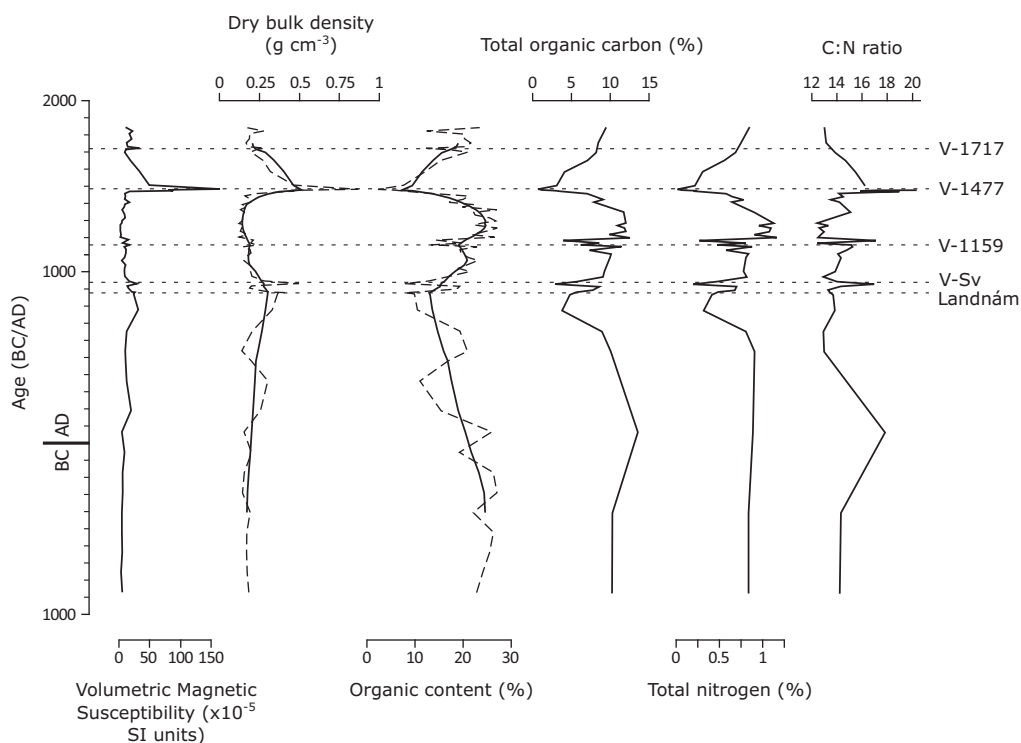


Fig. 4. Sedimentological data for Kalmanstjörn. The dry bulk density and organic matter records are presented as raw data (the dashed line) and a 10-point moving average (the thick black line).

arboreal pollen and increased dominance of heathland and herbaceous taxa (Fig. 5A). *B. pubescens* percentages decline from 40 to 15% over approximately 10 years at the base of the zone and then show little variability. This reduction is accompanied by a sharp increase in Cyperaceae, from 25 to 45%, over the same time scale. *B. nana*, *Empetrum nigrum* and *Thalictrum* also show small-scale percentage increases at this time. Poaceae retains similar percentages to KMN-1. *Salix* maintains values from KMN-1b (except for a sharp, short-lived decrease to <1% at AD 1750), and *Juniperus communis* appears sparsely after AD 1580. Members of the Apiaceae family become rare after AD 1480.

Terrestrial spores increase in importance in KMN-2 (Fig. 5B). *Lycopodium annotinum* and *Selaginella selaginoides* both immediately increase to >5% and remain at these levels for the rest of the zone. *Sphagnum* shows a slight increase at the same time. Continued minor *Sordaria* occurrences, and a single occurrence of HdV-172 (*Coniochaeta lignaria*), represent the coprophilous fungal spore assemblage of the zone. Aquatic species decline rapidly above the V-1477 tephra layer: of the two most abundant aquatic taxa, *Isoetes* returns to KMN-1a levels and *Myriophyllum alterniflorum* declines to its minimum values in the record (<2%). Both aquatic taxa show a sharp increase after AD 1750.

#### Concentrations and accumulation rates

Figure 6 shows summary data for concentrations and accumulation rates of the three main categories of taxa (terrestrial pollen, aquatic pollen and spores, and *Pediastrum* colonies) and the dominant taxon in each category (*Betula pubescens*, *Myriophyllum alterniflorum*, and *Pediastrum boryanum* undiff., respectively). Terrestrial pollen concentrations follow the same broad trends as the percentage data and are relatively consistent except for sharp decreases where tephra layers occur. Accumulation rates of terrestrial pollen increase from <150 grains  $\text{cm}^{-2} \text{a}^{-1}$  in KMN-1a to >500 grains  $\text{cm}^{-2} \text{a}^{-1}$  in KMN-1b, before declining in KMN-2.

Concentrations and accumulation rates of aquatic pollen and spores closely follow the *M. alterniflorum* percentage trends; low values dominate in KMN-1a, higher values in KMN-1b, and low values in KMN-2. *Pediastrum* colony data, on the other hand, show a permanent increase from the base of KMN-1b. Low values in KMN-1a (<4000 colonies  $\text{cm}^{-3}$  and <100 colonies  $\text{cm}^{-2} \text{a}^{-1}$ ) are followed by markedly higher concentrations (5000–16 000 colonies  $\text{cm}^{-3}$  and 500–2000 colonies  $\text{cm}^{-2} \text{a}^{-1}$ ) in KMN-1b, with the lowest values coinciding with tephra layers. Concentrations maintain these values in KMN-2, whereas accumulation rates drop to ~300 colonies  $\text{cm}^{-2} \text{a}^{-1}$ .



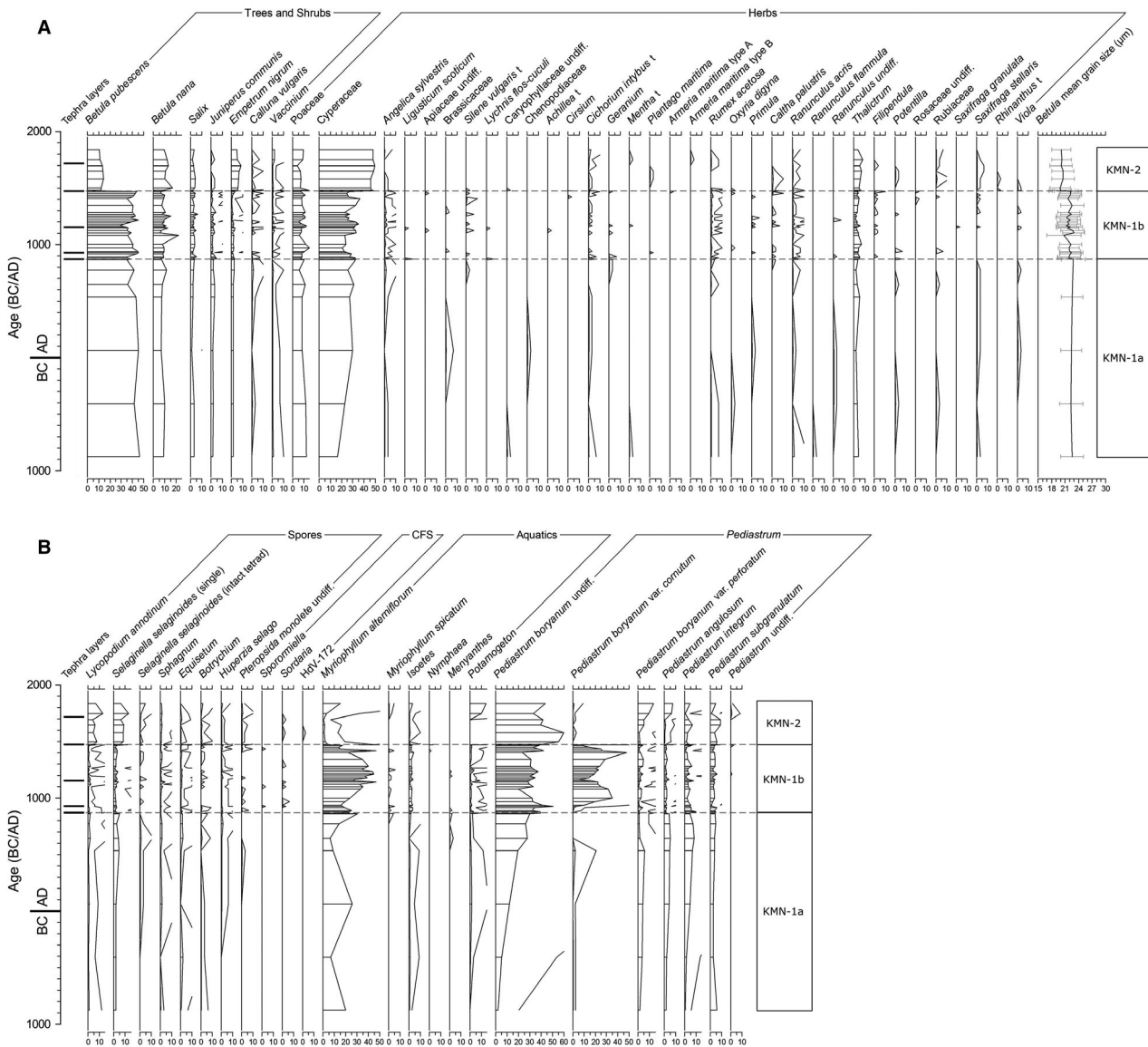


Fig. 5. A. Terrestrial pollen percentage data for the Kalmanstjörn record with 10× exaggeration lines. Size measurements of *Betula* grains (with 1 standard deviation) are also presented. B. Non-pollen palynomorph percentage data for the Kalmanstjörn record with 10× exaggeration lines. CFS = coprophilous fungal spores. Dated tephra horizons (representing primary tephra deposition) are marked on both (A) and (B).

### Pollen preservation

The *Betula pubescens* pollen preservation data show two distinct periods (Fig. 7). Below the V-1477 tephra layer (in KMN-1a and KMN-1b), on average less than 20% of *B. pubescens* grains are damaged. Inter-sample variability is noticeably greater above the LTL (in KMN-1b) than below it, but this is partly a consequence of higher sampling resolution and increased sedimentation rates. Instances of increased damage frequently coincide with tephra deposition. Above V-1477 (in KMN-2) the proportion of damaged grains increases permanently to 40–50%. Throughout the record (and most prominently in KMN-2) the most common types of

damage to *B. pubescens* grains are folding/crumpling and degradation.

### Interpretation and discussion

#### Terrestrial vegetation

*Pre-settlement environment (850 BC–AD 877).* – The pre-settlement environment is characterized by stable pollen spectra dominated by high proportions of *Betula pubescens* and with very little variability in any taxa. *B. pubescens* pollen consistently exceeds 40% of the assemblage, which could be interpreted to represent widespread woodland in the vicinity of the lake.

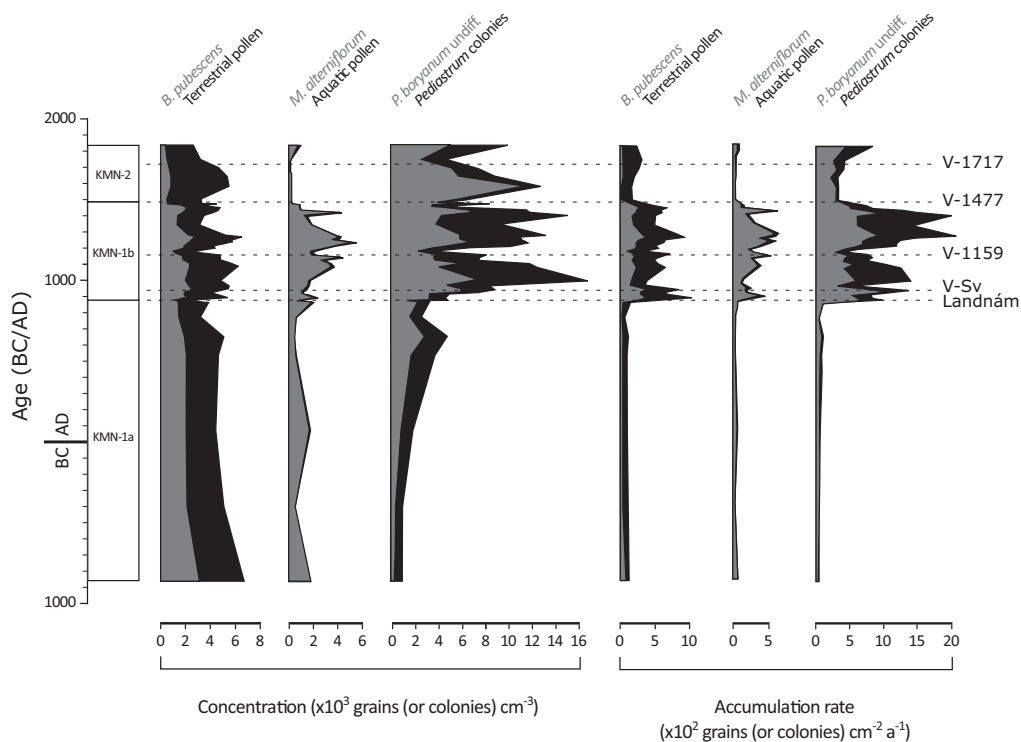


Fig. 6. Concentration and accumulation rate data for selected taxa (*Betula pubescens*, *Myriophyllum alterniflorum* and *Pediastrum boryanum* undiff.) and for each category of taxa (terrestrial pollen, aquatic pollen and spores, and *Pediastrum* colonies).

However, the *B. pubescens* pollen accumulation rate is low by comparison with measurements of modern pollen accumulation rates in Scandinavia, suggesting that *B. pubescens* populations at Kalmanstjörn might in fact have been more sparse and/or distant than would be inferred from the pollen percentage alone. Lake surface sampling and pollen trap data have been used to identify palynological influx values that can signal the local presence of *Betula* populations in Scandinavia. For example, a presence/absence threshold of 250 grains  $\text{cm}^{-2} \text{a}^{-1}$  has been identified in core-top sediments (Seppä & Hicks 2006), while data from pollen traps suggest that a site within a dense birch woodland could exceed accumulation rates of 1500 grains  $\text{cm}^{-2} \text{a}^{-1}$  (Hicks & Hyvärinen 1999). However, there is some evidence that suggests that *Betula* accumulation rates in Iceland are consistently lower than in Scandinavia (Hättestrand *et al.* 2008). During the pre-settlement period in the Kalmanstjörn record, *B. pubescens* accumulation rates never exceed 100 grains  $\text{cm}^{-2} \text{a}^{-1}$ , and the combined accumulation rates of *B. pubescens* and *B. nana* exceed 100 grains  $\text{cm}^{-2} \text{a}^{-1}$  in only one sample. In this, the Kalmanstjörn record is similar to the Helluvaðstjörn record, in which pre-settlement accumulation rates of *B. pubescens* likewise fall consistently below 100 grains  $\text{cm}^{-2} \text{a}^{-1}$  (Lawson *et al.* 2007). There is a large amount of independent evidence that

woodland was widespread in Mývatnssveit immediately after settlement when resource utilization can be detected in records, including charcoal pits, charcoal lenses in archaeological contexts, and macrofossil assemblages (Lawson *et al.* 2009), at a time in which the Kalmanstjörn record continues to record high proportions of *B. pubescens* pollen (see below). Given that the pre-settlement pollen assemblages so closely compare with the post-settlement assemblages in which there is independent evidence for local and regional woodland populations, and the evidence that local *Betula* populations in Iceland can produce markedly less pollen than Scandinavian populations (Hättestrand *et al.* 2008), we interpret the Kalmanstjörn record to show that the pre-settlement environment was characterized by widespread woodland populations on both a local and regional scale.

Between *c.* AD 100 and *Landnám* (AD 877) the proportion of *B. pubescens* grains showing evidence of corrosion and degradation increases. Pollen that has been deposited and stored in soils typically shows signs of chemical damage caused by bacterial and fungal attack, and grains that are subsequently remobilized may suffer mechanical damage (Cushing 1964, 1967; Havinga 1967). Therefore, the preservation data indicate that there was increased reworking of soils containing non-contemporaneous pollen grains into

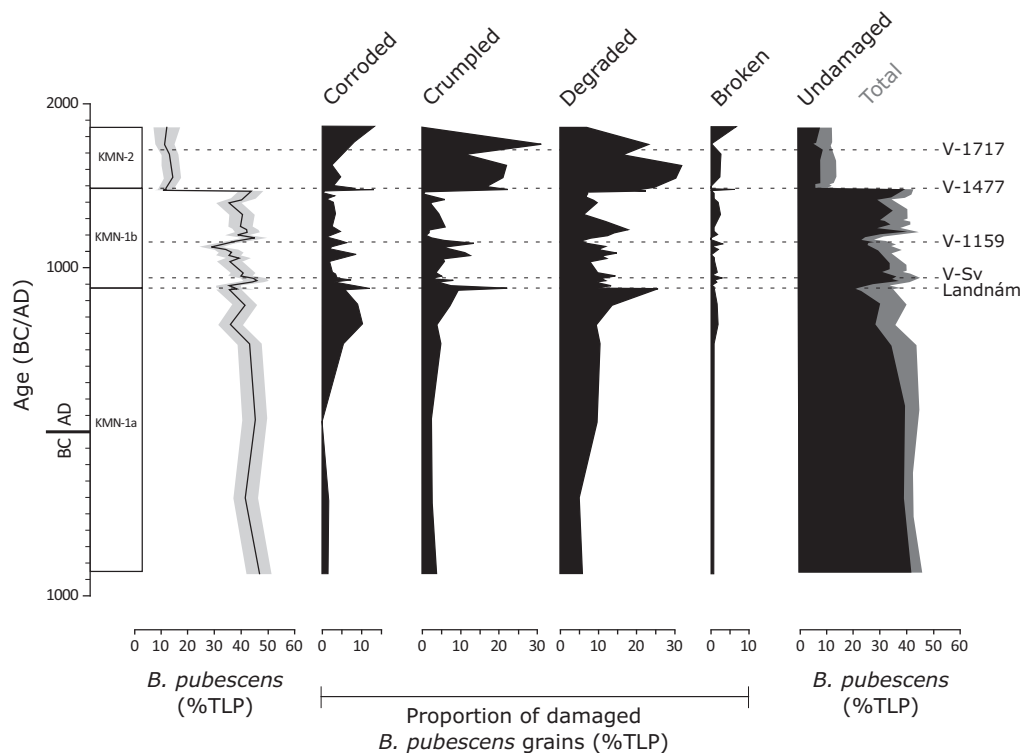


Fig. 7. *Betula pubescens* proportions as per Fig. 5, with 2 standard deviation confidence intervals (after Maher 1972); the proportion of *B. pubescens* pollen grains in each of the four categories of damage; and the number of well-preserved/undamaged *B. pubescens* grains as a proportion of the TLP assemblage, with the total *B. pubescens* proportions as per Fig. 5 for reference.

the lake. It is most likely that woodland in the hydrological catchment contracted and exposed soils to erosional processes. This could perhaps have been caused by increased wetness of soils creating unfavourable conditions for *B. pubescens* growth (Bartley 1973). Alternatively, woodland contraction and increased mobility of soils may have been caused by cooling climatic conditions. Increased soil mobilization beginning around AD 500 is a feature of a composite record from a number of lake records in western Iceland, coinciding with evidence for increasingly cold and harsh climatic conditions (Geirsdóttir *et al.* 2020). This correlates with a composite of 25 *Betula* undiff. records that shows a gradual decline in *Betula* pollen abundance starting around 100 BC, suggesting that these large-scale environmental conditions were affecting vegetation across much of the island (Streeter *et al.* 2015).

*Post-settlement preservation of woodland (AD 877–AD 1477).* – In the context of the existing palaeoenvironmental data from Mývatnssveit and from the wider Icelandic context, which for the most part show deforestation by AD 1300, the most intriguing element of the Kalmanstjörn record is the persistence of abundant *B. pubescens* pollen until AD 1480, nearly 600 years after the area was first settled. The pollen assemblages show remarkable stability across the

*Landnám* horizon, and throughout KMN-1a and KMN-1b the *B. pubescens* pollen counts consistently fall within the statistical uncertainty between samples (Fig. 7). The only exceptions to the stability of the pollen record are what appear to be low-magnitude and short-lived responses to the deposition of the V-Sv (AD  $938 \pm 6$ ) and V-1159 tephra layers where counts lie outside of inter-sample variability. These responses probably reflect changes in substrate conditions that led to increased growth rates and pollen productivity of herbaceous taxa, thereby reducing the relative abundance of *B. pubescens* pollen (Edwards *et al.* 2004; Payne *et al.* 2013). As this overall stability is unusual in post-settlement Icelandic pollen records, it is important to establish whether the pollen assemblages (and, in particular, the *B. pubescens* record) could be reflecting any processes other than the persistence of woodland. Firstly, the climatic developments of the MWP and LIA may have affected pollen productivity. The MWP was a period of increased average temperatures in the North Atlantic region that may have started around AD 800 in Iceland, while the LIA was a cooler, drier and windier period that began between AD 1250 and AD 1300, with intensification after AD 1400 or AD 1450 (Moberg *et al.* 2005; Geirsdóttir *et al.* 2009). Although little data are available, *B. pubescens* pollen productivity in Iceland

has been positively correlated with temperature (Hallsdóttir 1999). Therefore, increased pollen productivity during the MWP could maintain high *B. pubescens* proportions in pollen assemblages even as trees were being felled (cf. Erlendsson & Edwards 2009). However, this is unlikely for two reasons. There is no sign of an increase in *B. pubescens* in any of the three data forms (proportion, concentration, and accumulation rate; Figs 5, 6) in the period of the MWP just before settlement (AD 800–877). There is also no sign of a reduction in *B. pubescens* in any of the three data forms after AD 1250 when the climate began to cool, which suggests that *B. pubescens* percentages have not been substantially affected by climatic conditions. Secondly, high *B. pubescens* percentages in the record may be artificially increased by the influx of non-contemporaneous grains delivered to the lake by the reworking of soils (particularly in a landscape denuded of trees). However, proportions of damaged *B. pubescens* grains remain low and C:N ratios remain stable, indicating that there were no prolonged periods in which there was increased delivery of terrestrial material into the lake (Meyers & Ishiwatari 1993; Meyers 2006). Therefore, it is unlikely that reworking of old pollen grains has substantially altered the pollen assemblages between settlement and AD 1480.

The pollen abundance data, therefore, strongly indicate that there was long-term persistence of woodland near Kalmanstjörn between the *Landnám* (AD 877±1) and V-1477 (AD 1477) tephra layers. Whether this was an accidental outcome of land-use decisions, or whether it represents an intentional preservation effort, can be assessed using the available data. There are sporadic occurrences of coprophilous fungal spores (*Sordaria* and *Sporormiella*) after *Landnám*, which may indicate that herbivores were allowed to freely move in the nearby catchment (Fig. 8). Coprophilous fungal spores are not widely dispersed due to their production near the ground, and therefore, they can be taken to represent herbivore presence very close to the lake (Van Geel *et al.* 2003). Given the limited evidence for landscape instability that could have transported more distal spores into the lake, the coprophilous fungal spore record can be taken to indicate a local introduction of herbivores on at least a limited scale, which would be expected to have a negative impact on woodland populations (e.g. Aradóttir & Arnalds 2001). However, other evidence suggests that woodland was intentionally protected. There are abundant charcoal production pits near the lake and in the region as a whole, dating late into the settlement period, which indicates that people were using the woodland for resources in a long-term, sustainable manner (Church *et al.* 2007; McGovern *et al.* 2007; Lawson *et al.* 2009). Additionally, throughout the region there are the remains of wall

structures that were in use between the 10th and 12th centuries in part constructed to separate exclusive land from the communal grazing lands (*affretir*) (Einarsson 2015). Such wall structures are extensive in the Laxárdalur and Rekyjadalur valleys and indicate that efforts were being made to manage the use of the landscape between the two rivers (the Kalmanstjörn catchment), which, based on the archaeological record, would have been of interest to a large number of different farms (Vésteinsson & McGovern 2012; Einarsson 2015). Finally, despite the fungal spore occurrences, grazing tolerant taxa that would indicate the presence of herbivores remain rare. It is likely that the vegetation signal is more robust than the coprophilous fungal spore data, which are not always a clear proxy for herbivore abundance (Gill *et al.* 2013; Tisdall *et al.* 2018; Davies 2019). On the balance of evidence, it is, therefore, most probable that efforts were made to protect the local woodland resources, with perhaps only low-density grazing occurring in the area surrounding Kalmanstjörn.

*Significance of long-term preservation of woodland in Mývatnssveit and Iceland.* – The long-term preservation of woodland indicated by the Kalmanstjörn record supports other records from the Mývatnssveit region. The current understanding of the vegetation history of Mývatnssveit is that, on the eve of settlement, some areas had extensive woodland cover whereas other areas (particularly meadows and bogs; cf. Lawson *et al.* 2009; Barclay 2016) were largely unwooded. After settlement, these patterns continued largely unchanged, with woodland persisting for centuries. The Helluvaðstjörn lake record and a peat profile from the Grænavatn estate indicate that woodland extent slightly decreased just after *Landnám* but was largely preserved until AD 1300, when it dropped to present levels (Lawson *et al.* 2007; Colquhoun *et al.* 2010). A peat profile from the Hofstaðir estate indicates that *Betula* populations survived locally until AD 1790 (Tisdall *et al.* 2018). The Kalmanstjörn record contributes to a growing story in which deforestation around Lake Mývatn was temporally and spatially variable. The area was settled rapidly (Vésteinsson & McGovern 2012), and yet rapid clearance of land is not seen in any palaeoecological record from the region (although there are few chronologically robust records with high temporal resolution). It is likely that the pre-settlement environment was patchy, and those areas that were already largely free of woodland (see the meadows of Gautlönd and Viðatoft, and bogs such as Hrisheimar; Fig. 1) were preferentially targeted for the first settlements (Vésteinsson 1998; Lawson *et al.* 2009; Barclay 2016). After settlement, efforts were made to use woodland resources sustainably and woodland was preserved initially on a large scale (represented by the Helluvaðstjörn and Kalmanstjörn records) and, when

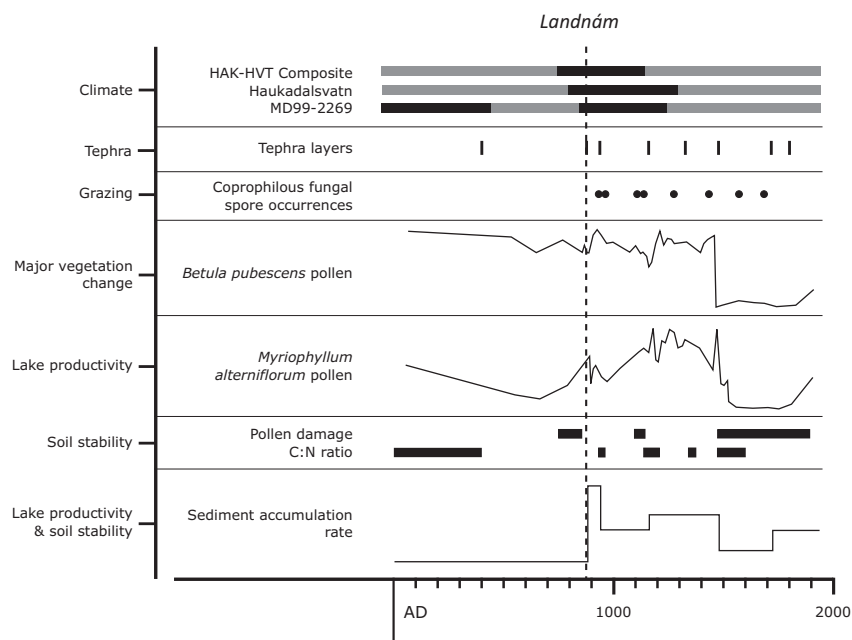


Fig. 8. Summary diagram for the Kalmanstjörn record synthesizing the major ecosystem changes (*Betula pubescens* pollen percentage, *Myriophyllum alterniflorum* pollen percentage, soil stability proxies of pollen damage and C:N ratio, and sediment accumulation rates) and possible drivers (climate, tephra deposition, and coprophilous fungal spore occurrence). Climate data from the Haukadalsvatn-Hvítarvatn composite (Geirsdóttir *et al.* 2013), Haukadalsvatn (Geirsdóttir *et al.* 2009), and marine core MD99-2269 (Cabedo-Sanz *et al.* 2016). Grey represents cooler periods, black indicates warmer periods. For soil stability proxies, black bars represent pollen damage (where the proportion of damaged *B. pubescens* grains exceeds 20%) and C:N ratios (where there is a clear increase from the prevailing conditions).

those resources were depleted, on local (farmstead) scales (represented by the Hofstaðir record).

Such persistence of woodland after settlement is a rare scenario in other parts of Iceland. The only lake record outside of Mývatnssveit that indicates long-term woodland preservation is Breiðavatn in west Iceland, where woodland persisted until AD 1200 (Gathorne-Hardy *et al.* 2009). Additionally, a number area of charcoal production pits in the Eyjaffjallahreppur area in the south of Iceland have been dated to two distinct time periods: from *Landnám* to the 11th century, followed by a hiatus, then from the late 12th to late 13th centuries (Church *et al.* 2007). This indicates that woodland must have survived in this region until at least the late 13th century. Most other regions in Iceland preserve evidence for rapid loss of woodland. Early research prioritized sites close to early farms, which are more likely to show early localized woodland clearance (Þórarinnsson 1944; Einarsson 1961, 1963). More recent studies support the conclusion of rapid deforestation in at least some locations, including in the Mosfell valley in the southwest (Pétursdóttir 2014; Riddell 2014; Riddell *et al.* 2018b) and Helgutjorn in the east (Jónsson 2009). A lake record from Vatnskotsvatn in the north shows deforestation before AD 950, which indicates rapid catchment-scale deforestation (Hallsdóttir 1995). Whether long-term and large-scale preservation

of woodland is, therefore, a story unique to the Mývatnssveit region remains to be seen as further studies are carried out in other parts of Iceland.

#### *Fifteenth-century deforestation (AD 1477–AD 1850).* –

It is not until after the deposition of the V-1477 tephra layer that the Kalmanstjörn record shows evidence of pronounced terrestrial change. In as little as 10 years, the woodland area contracted and was replaced by vegetation similar to that found in the lake catchment today: sedge communities around the lake margin and heathland beyond. Given the speed of the ecosystem transition, and without widespread burning (for which there is no evidence in the charcoal record), it is probable that direct clearance was in part responsible for the deforestation. At the same time, the increase in grazing-resistant taxa (such as *Selaginella selaginoides* and *Thalictrum*) and reduction in those susceptible to grazing (particularly *Angelica* spp.) indicate that grazing increased in intensity (Tisdall *et al.* 2018; Davies 2019). Both of these lines of evidence suggest that the local land use rapidly changed from one of low-intensity use to one of higher intensity resource utilization for the first time in its 600 years of settlement history.

Such a large change in local land use suggests that there was a change in the pressures on the local farmers. One external pressure was likely the climatic change in the LIA. The Icelandic climate began to cool from

c. AD 1250, with the trend intensifying after c. AD 1450 (Geirsdóttir *et al.* 2009). Such cooling may have increased the demand for woody resources (e.g. for fuel), and the woodland around Kalmanstjörn would have represented a prime (and rare) source in the late 15th century. Additionally, the cooling climate (exacerbated by the deposition of the thick V-1477 tephra) led to widespread landscape degradation in the highlands to the south of Lake Mývatn (Ólafsdóttir & Guðmundsson 2002; Vésteinsson *et al.* 2014). Degradation reduced the amount of viable land in communal grazing areas, and livestock would have needed to be relocated to suitable rangeland sites at lower altitudes (such as Kalmanstjörn). The increase in livestock populations would have damaged *Betula* seedlings, preventing the replacement of lost trees (Gill 1992; Aradóttir & Arnalds 2001). Compounding this, the cooler temperatures slowed the growth of those seedlings that survived, further slowing the replenishment of woodland stocks (Wastl *et al.* 2001; Weih & Karlsson 2001). The cumulative impacts of these interlinked changes ultimately led to the regime shift seen in the Kalmanstjörn record: a sudden collapse in woodland cover.

Previous research has suggested that deforested woodlands in Iceland were typically replaced by one of two ecosystems. Where early clearance was followed by an expansion of Poaceae it has been taken to represent the establishment of infields, where fodder and sometimes cereals were grown, and outfields, where animals were permitted to graze (Smith 1995; Dugmore *et al.* 2005; Sveinbjarnardóttir *et al.* 2007). Elsewhere woodland was replaced by heathland taxa, which has been taken to represent marginal sites where little active land management occurred (Lawson *et al.* 2007). At Kalmanstjörn, *Betula pubescens* was replaced by *Empetrum nigrum*, *Lycopodium annotinum* and *Selaginella selaginoides* in the catchment, which we infer to indicate that open heathland environments dominated. *E. nigrum* and *S. selaginoides* are also acidophilic, suggesting that soils were in an acidic state after deforestation. Elsewhere, it has been suggested that the opening of the canopy and the resultant penetration of rainfall after deforestation contributed to leaching and soil acidification (cf. Lawson *et al.* 2007). At Kalmanstjörn, where acidification immediately followed deforestation, it is unlikely that deforestation led to acidification. Instead, acidification was probably caused by the impacts of the deposition of the V-1477 tephra. The large magnitude of this event would have caused soil acidification via acid precipitation (Payne & Blackford 2005). Unlike in the majority of post-settlement Icelandic records, Poaceae never exhibits a sustained increase in extent at Kalmanstjörn. A low-magnitude, short-lived increase in Poaceae coincides with the V-1477 tephra, which probably reflects a short-lived period in which the

tephra created a dry substrate before it was either incorporated into the soils or eroded (Edwards *et al.* 2004; Payne *et al.* 2013). Similar short-lived increases that coincide with tephra layers occur throughout the succession. The lack of any permanent change in Poaceae pollen abundance supports other lines of evidence (above) that Kalmanstjörn has always represented a largely unmanaged site that was never the location for infields or outfields. Instead, Kalmanstjörn has primarily been used as grazing lands, with grazing intensity varying through time.

#### *Aquatic ecosystem*

At the start of the record, the Kalmanstjörn aquatic ecosystem was for the most part a moderately productive ecosystem. *Myriophyllum alterniflorum* dominated the macrophyte assemblage and remained broadly stable within a 10% range and most *Pediastrum* taxa were present with little variability between samples. There is indication that the system slowly began to increase in productivity from c. AD 50 onwards; *M. alterniflorum* increases to its maximum pre-Landnám value, albeit for only one sample, and a number of *Pediastrum* taxa show gradual increases in abundance. AD 50 broadly coincides with the increase in the proportion of damaged *B. pubescens* grains in the record and indicates that there was likely an increase in the nutrients being delivered by influxes of soils into the lake (see above; Mills *et al.* 2017). The fact that *Pediastrum* taxa show a sustained increase in abundance while the aquatic macrophyte population soon returned to lower values may indicate that the two groups have different sensitivities, and perhaps that initial influxes of nutrients that were sufficient for the enhanced growth of macrophyte populations were not sustained.

The aquatic record shows evidence of substantial and sustained change only after the deposition of the LTL (AD 877±1), reaching the highest values of macrophyte abundance in the record after AD 1000. This marks a clear decoupling between the aquatic system and the terrestrial system, which shows limited change above the LTL. The increase in *M. alterniflorum* pollen, in combination with the increased organic content of the sediment, indicates that macrophyte biomass increased substantially shortly after Landnám (Edwards *et al.* 2000). While this may have been driven in part by the climatic amelioration of the MWP, given the timing it is quite likely that settlement processes were also involved in increasing lake productivity. The introduction of browsing mammals including goats and cattle would have provided a new route for the nutrients held in trees and shrubs to be introduced into streams and lakes. A similar pattern of increased aquatic productivity was identified at Helluvaðstjörn, which showed the same disconnect



between the terrestrial and aquatic systems (Lawson *et al.* 2007), and in other parts of Iceland (Gathorne-Hardy *et al.* 2009; Jónsson 2009). On the Faroe Islands (Hannon *et al.* 2005; Lawson *et al.* 2005), a similar aquatic response to human settlement in an environment lacking large tree populations provides further support to two dominant conclusions: that the introduction of grazing animals was the dominant driver of large-scale aquatic ecosystem changes; and that aquatic environments may be more sensitive to initial human disturbances than terrestrial environments in parts of the North Atlantic island chain.

Macrophyte productivity began to decline around AD 1270, and the rate of decline increased across the V-1477 horizon (just as woodland rapidly declined). The aquatic and terrestrial systems continued to be decoupled; although there is evidence (in the pollen preservation and C:N ratio data) in the Kalmanstjörn record for large-scale terrestrial vegetation changes and landscape instability in response to changes in human activity after AD 1477, the aquatic ecosystem does not straightforwardly reflect these terrestrial processes. Instead of increasing in response to the influxes of nutrients from increased local herbivore populations and soils, aquatic productivity decreases, counterintuitively. The decline in aquatic productivity from *c.* AD 1270 coincides with the onset of the LIA (Geirsdóttir *et al.* 2009). The LIA was probably the coolest period of the 3000 years represented by the Kalmanstjörn record (Geirsdóttir *et al.* 2009; Blair *et al.* 2015; Cabedo-Sanz *et al.* 2016). It is, therefore, likely that cooling climatic conditions led to increased lake ice cover which would limit light penetration and the remobilization of nutrients stored in lake sediments, in turn reducing productivity (Rouse *et al.* 1997; Lotter & Bigler 2000; Ohlendorf *et al.* 2000; Schmidt *et al.* 2008). The response of the Kalmanstjörn aquatic system bears similarities to other aquatic records from Iceland that cover earlier cooling events. For example, in northwest Iceland cooling after the Holocene Thermal Maximum is associated with a reduction in *Myriophyllum alterniflorum* pollen at Kagaðarhóll and Barðalækjartjörn (Eddudóttir *et al.* 2015, 2016). The additional impacts of the deposition of the V-1477 tephra layer probably exacerbated the impacts of the long-term cooling; it very likely damaged vegetation and reduced light penetration by increasing turbidity in the lake. Furthermore, the deposition of such a thick tephra layer would have separated the bed of the lake from the water column, preventing the remobilization of sediment and nutrients into the water column and thereby limiting productivity (Telford *et al.* 2004). The rapid decrease in productivity may indicate that tephra was a driver of change in an ecosystem that was already becoming increasingly vulnerable during the LIA. The evidence suggests that from the start of the LIA it was climate,

rather than human activity, that was the dominant driver of aquatic ecosystem changes, even after AD 1477 when the terrestrial system underwent rapid change and soils were increasingly reworked into the lake. The contrast between the terrestrial and the aquatic systems highlights their differing sensitivities to environmental drivers, which has significant implications for understanding past environmental systems dynamics in Iceland.

## Conclusions

The Kalmanstjörn record contributes significantly to the understanding of vegetation change after settlement in Iceland. It is the first pollen record generated from a lake sequence to show catchment-scale preservation of woodland until the late 15th century and indicates that the Norse settlers in this region maintained a larger stock of woodland resources than exist today until long after settlement (*c.* 600 years) and the onset of the LIA (*c.* 200 years). The terrestrial pollen data indicate a largely stable ecosystem with little change in either the woodland or minor taxa, and little soil erosion until AD 1477, despite evidence for grazing herbivores in the landscape. After the deposition of the V-1477 tephra, woodland rapidly declined, the local area became dominated by grazing-resistant rangeland and wetland taxa, and soil erosion increased, all probably reflecting a change in human land management in the area such as a substantial intensification of grazing.

The Kalmanstjörn record also provides evidence supporting the idea that settlement quickly led to a substantial change in the lake ecosystem. As at Helluvaðstjörn, there is a lack of evidence for soil erosion, which suggests an alternative mechanism must be responsible, such as increased rates of nutrient cycling by livestock. It appears that, at this site, the palaeolimnological record is more sensitive than terrestrial pollen to the first impacts of settlement, a conclusion that may also be applicable in areas with more cryptic settlement histories.

The study has generated a comprehensive data set aimed at investigating multiple different drivers of environmental change in Iceland, with the aim of better disentangling the causal mechanisms contributing to system development. The terrestrial system was dominated by land-use decisions from *Landnám* onwards, whether that was a decision to preserve or to utilize the woodland resources. There is little evidence for terrestrial vegetation change as a direct response to climatic change. Widespread soil erosion began after AD 1477, but it is unclear whether deforestation or harsher climates drove this change. The aquatic system was also driven into a more productive state by the introduction of new sources of nutrients after settlement, but during the LIA the lake system became increasingly dominated by climate. Understanding the interactions between

anthropogenic and climatic drivers remains a complex issue in palaeoenvironmental research, and Iceland represents an ideal location in which to further investigate these relationships

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*Author contributions.* – All authors designed the study. ITL & KHR completed fieldwork. WH completed data collection. All authors contributed to writing of the manuscript.

*Data availability statement.* – Palynological data have been submitted to the European Pollen Database.

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## Supporting Information

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

*Table S1.* Tephra geochemical data for analysed tephra layers in the Kalmanstjörn record.

*Table S2.* Tephra geochemical data for the BCR2g and Lipari standards that were analysed during sample analyses.