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A multiple profile approach to the palynological reconstruction of Norse landscapes in Greenland's Eastern Settlement

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ABSTRACT

Palynological research is increasingly revealing the landscape impacts of Norse colonisation in southern Greenland. Typically, although not exclusively, these studies are from depositional environments with highly localised pollen source areas close to fjord-side centres of medieval power. In contrast, this paper presents data from Vatnahverfi, an inland district of the Eastern Settlement, and explores the emergence of a cultural landscape through three pollen sequences at variable distances from Norse farms. Two are from mires with small pollen source areas close to (<100 m) and distant from (≥1500 m) probable farming activities. The other provides a more regional signal of vegetation change, albeit one located close to a Norse settlement. *Landnám* is marked primarily through an increase in microscopic charcoal and the appearance of pollen from *Rumex acetosella*, although significant differences between profiles are noted. Close to Norse ruins, pollen productivity from grassland communities increases and woodland and scrub representation declines. Further from archaeological remains, palynologically inferred human activity is primarily characterised by decreased productivity, notably declining influx from woodland and scrub species, reflecting grazing herbivores or coppicing. Abandonment of Vatnahverfi is indicated from the late 14th to early 15th century AD.

Introduction

In the late 8th century AD, Norse settlers, primarily from southwestern Norway, initiated a widespread expansion into the North Atlantic region, reaching the Faroe Islands around AD 825 (Jones, 1984), Iceland c. AD 870 (Vésteinsson and McGovern, 2012) and Greenland c. AD 985 (Seaver, 2010). This expansion is frequently assumed to be correlated to the Medieval Warm Period of the late 10th to early 11th centuries, when temperatures in the North Atlantic were similar to, or just below, the mean levels of the 1961–1990 interval (Vinther et al., 2010). Pastoral agriculture – centred on the rearing of cattle, sheep and goats for meat and milk (McGovern, 1985) – was introduced into pristine subarctic environments and supplemented by the hunting of wild game. Cultural landscapes supporting agricultural systems developed where people had hitherto been essentially absent (Dugmore et al., 2005; but see Church et al., 2013). Settlement in Greenland persisted until the mid-15th century AD and the reasons for abandonment continue to fuel debate (Seaver, 2010; Dugmore et al., 2012). Evidence for decreasing temperatures from the mid-14th century has traditionally been used to promote climatic change as the primary causal factor in the failure of Norse Greenland (Dansgaard et al., 1975). In recent years this explanation has become more nuanced with Dugmore et al. (2012), for instance, suggesting that the Norse Greenlanders successfully adapted to 14th century climatic change, but that these adaptations increased their vulnerability to economic change in the 15th century.

Norse settlement in the North Atlantic followed a dispersed pattern centred upon individual farm units. In southern Greenland farms were primarily situated to exploit areas of pasture and were concentrated towards the heads of the fjords which experience a longer growing season owing to a drier continental climate – with warmer summers and colder winters – than the more oceanic coastal reaches (Feilberg, 1984). The majority of farms were located along the coasts of the inner fjords, which eased access to both important routes of communication (Roussell, 1941) and the marine foods that were an integral part of Norse diet (Arneborg et al., 2012). Archeological investigations suggest that at a minimum each farm comprised a house, a byre for stalling animals, a barn for storing hay, and perhaps some subsidiary structures for storing food products (Roussell, 1941). Yet direct knowledge of the cultural landscapes created by this farming activity is limited by a lack of documentary sources pertaining to Norse Greenland. For a conceptual understanding of how the landscape was managed, it is necessary to turn to the extant societies of the North Atlantic (cf. Roussell, 1941; Albrethsen and Keller, 1986; Vésteinsson et al., 2002). In Iceland, the

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Faroes and the Norse homelands of western Norway, a system known as the infield/outfield system was well developed (Øye, 2001). The infield – or homefield – was the area within the immediate vicinity of the buildings where during the summer months hay would be grown to support the overwintering of livestock. Beyond the infield was the outfield, where animals would graze during the summer months (Borchgrevnik, 1977; Øye, 2001, 2005). The outfield was also an area where supplementary fodder and firewood resources were collected (Øye, 2005); activities often associated with subsidiary farming units such as shielings (Ledger et al., 2013).

Recent years have witnessed renewed interest in the paleoenvironmental impacts of Norse *landnám* (see Edwards et al., 2004, 2009) building on the earlier work of Fredskild (1973, 1978). With the exception of Gauthier et al. (2010), later investigations have focused on contexts with local pollen source areas (sensu Jacobsen & Bradshaw, 1981). Despite furnishing a wealth of high-resolution information on farming within the infield areas (e.g. Edwards et al., 2008, 2011a) these studies are heavily biased towards typical fjord-side farming locations.

In order to explore activities in inland areas, this paper presents three high-resolution pollen-analytical reconstructions from Vatnahverfi, an interior district of the Norse Eastern Settlement (Fig. 1). Two of these reconstructions are from mires where the relevant source area for pollen (RSAP) – defined as, 'the smallest spatial scale of vegetation that can be reconstructed from pollen records' (Sugita et al., 1999, p. 409) – is estimated to be a radius of 800–1000 m around the site, or far less (cf. Bunting and Hjelle, 2010; Bunting et al., 2013). These provide comparable, localised pictures of vegetation change that are used to examine Norse landscape impacts in both infield and outfield areas. The third profile, from a lake margin adjacent to Norse farm ruins, provides a more

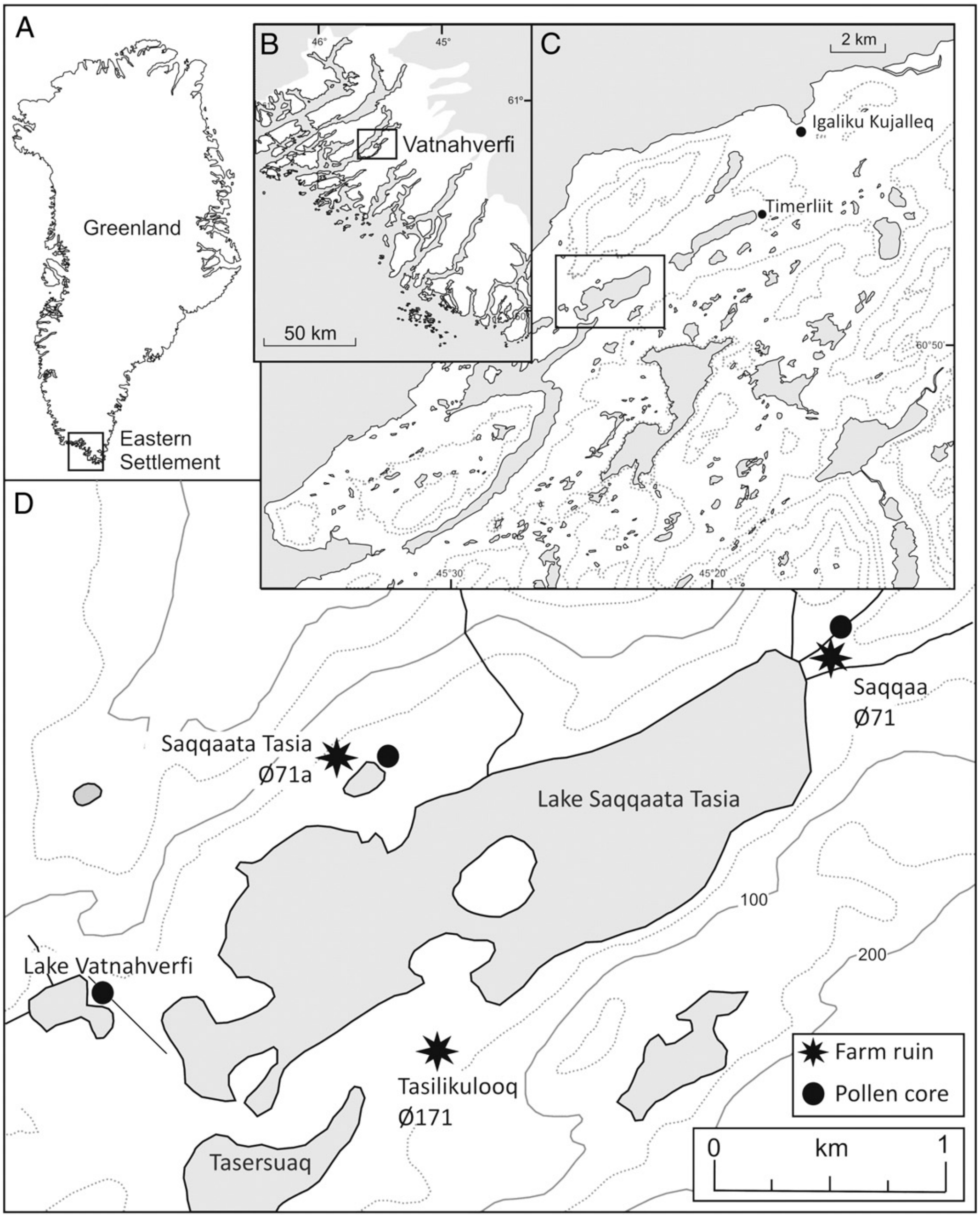

Figure 1. (A) Location of the Norse Eastern Settlement in Greenland; (B) Vatnahverfi within the Eastern Settlement; (C) Vatnahverfi; (D) the study sites within Vatnahverfi.

regional signal. In tracing how the emergence and senescence of this Norse cultural landscape is reflected in a variety of paleoecological contexts, this paper seeks especially to: (i) ascertain the intensity of the paleoecological signature for *landnám*; and (ii) explore the record of this past cultural landscape and the attendant human impacts evident at different spatial scales of analysis. Both aspects are related and are of key methodological interest to archeologists and palynologists.

Background

Vatnahverfi

Vatnahverfi ('land of lakes'; Ingstad, 1966) was a densely occupied area at the heart of the Norse Eastern Settlement (Fig. 1; Ledger et al., 2013, 2014). The topography is variable and dominated by a series of mountainous ridges divided by long valleys containing lakes. Relief ranges from sea level to >600 m asl, with local maxima over 1000 m asl. The geology is uncomplicated and dominated by granites of the Ketilidian Mobile Belt (c. 1.7–1.8 Ga). Overlying this basement geology are glaciofluvial deposits of Quaternary age (Feilberg, 1984). Climatically the site is within the subarctic, suboceanic belt of southern Greenland (Feilberg, 1984). The nearest observational data come from Narsarsuaq which experiences mean summer (July) temperatures of 9.8°C and annual precipitation of 696 mm for the period 1961–1990.

Sheep farming dominates the economy of Vatnahverfi and today there are seven sheep farms that exploit former Norse fields and pastures. Associated with these farms are hayfields and improved grasslands which supply the winter fodder for livestock. Beyond the immediate vicinity of the farms the dryland vegetation of the region is dominated by heavily grazed *Salix glauca*–*Betula glandulosa* scrub with rare patches of *Betula pubescens* woodland. Mires supporting *Carex* spp. and bryophytes are common around lakes, ponds and streams. Plant nomenclature follows Böcher et al. (1968).

Methodology

Site selection and sediment sampling

Shallow organic deposits were identified and sampled at three locations (Fig. 1) using an 8 cm diameter Russian corer. At two sites – Saqqaa and Lake Vatnahverfi – samples were obtained from small mires each with a RSAP of c. 1 km and which were selected to provide localised records of vegetation change. Saqqaa, the location of a modern sheep farm and the ruins of two Norse farms named the North and South Farm (Ø71; Bruun, 1896; Vebæk, 1992), was selected to represent the Norse infield. A core was taken from a small (95 × 40 m) area of *Carex rostrata* reedswamp approximately 60 m from the nearest ruins. Lake Vatnahverfi is the name given by us to a water body approximately 3.5 km southwest of Saqqaa where the nearest known Norse farm ruins are ≥1.5 km distant. This site was chosen to reflect the Norse outfield and a core was taken from a shallow pool in the surface of the mire fringing the lake. The third site – Saqqaata Tasia – lies between Saqqaa and Lake Vatnahverfi and is approximately 80 m from the ruins of a Norse farm (Ø71a, Fig. 1D). Here the core was taken in an area of reedswamp at the margin of an unnamed lake – measuring approximately 250 × 100 m – with a likely RSAP in the order of 3–5 km (cf. Hellman et al., 2009) and the deposits are considered to have recorded more regional vegetation changes.

The co-ordinates of sampling locations were recorded using a Garmin GPS handset and the core sections were protected in plastic guttering and wrapped in polythene before being returned to the University of Aberdeen where they were placed in cold storage (4°C). Subsampling was undertaken in the laboratory at 1 or 2 cm intervals, which over many sections of the cores equates to a multi-decadal resolution of 30 cal years or less. Loss-on-ignition (LOI) was measured following 3 h combustion at 550°C (Bengtsson and Enell, 1986).

Pollen analysis

Pollen samples were prepared using standard NaOH, sieving, acetolysis and floatation procedures (Moore et al., 1991; Nakagawa et al., 1998). *Lycopodium* tablets were added to allow the calculation of concentration and influx data (Stockmarr, 1971). Samples were suspended in silicone oil, mounted on slides, examined using a Nikon E400 light microscope at ×400 magnification, and counted until a sum of 500 total land pollen (TLP) had been achieved. Pollen and spores were identified using Moore et al. (1991) and modern reference material. Nomenclature follows Bennett et al. (1994) and Bennett (2014a) with taxa absent from these lists following Moore et al. (1991). *Betula* pollen was separated into tree (*B. pubescens*) and shrub (*B. glandulosa*) varieties using grain size diameter measurements (cf. Fredskild, 1973; Schofield and Edwards, 2011) with *Betula* pollen <20 μm classified as *B. glandulosa*. Cereal-type pollen was identified and categorised following Andersen (1978). Coprophilous fungal spores – derived from fungi that grow on animal dung – were identified using van Geel et al. (2003). Pollen diagrams were constructed using TILIA and TGView software (Grimm, 1993, 2014) with percentages based upon the TLP sum.

Charcoal analysis

Microscopic charcoal in pollen residues was quantified using a microscope eyepiece graticule at a magnification of ×400. Owing to the frequently high concentrations of charcoal, only the first 50 fragments larger than 50 μm^2 were included in the analysis (cf. Edwards et al., 2008; Schofield et al., 2008). Methods employed for determining pollen concentrations were also used to calculate charcoal influx (cf. Swain, 1978). Charcoal to pollen (C:P) ratios were calculated to check whether charcoal abundances were changing as a consequence of sedimentation effects (Patterson et al., 1987).

Numerical analysis

Local pollen assemblage zones (LPAZs) were assigned with the aid of CONISS (Grimm, 1987) following square root transformation of percentage data. Rarefaction analysis (Birks and Line, 1992) was performed in *psimpoll* (Bennett, 2014b). Principal component analysis (PCA; Fig. 2) was undertaken on a site by site basis using CANOCO 4.5 (ter Braak and Šmilauer, 2002) after detrended correspondence analysis indicated linear rather than unimodal patterns for the datasets (Lepš and Šmilauer, 2003). In addition, PCA was run on a merged dataset that included pollen samples from all three sites. This appeared to offer little extra information and the results are not presented here.

Radiocarbon dating

Fifeteen plant macrofossil samples (Table 1) were submitted for AMS ^{14}C dating. Sediment samples were gently disaggregated in weak NaOH and washed through a 125 μm sieve. Residues were examined under a low power binocular microscope and plant macrofossils picked for dating. Seeds were identified using Cappers et al. (2006) and modern reference material, while wood was identified using thin section analysis (Hather, 2000). AMS samples were processed and measured at SUERC, East Kilbride, and calibration undertaken using the IntCal09 calibration curve (Reimer et al., 2009) and CALIB v6.0. Both Bayesian (*Bacon*; Blaauw and Christen, 2011) and classical (*Clam*; Blaauw, 2010) methodologies were explored for constructing age–depth models. Wherever possible, *Bacon* was used over *Clam* as the Bayesian approach provides more robust estimates of uncertainty than classical methods.

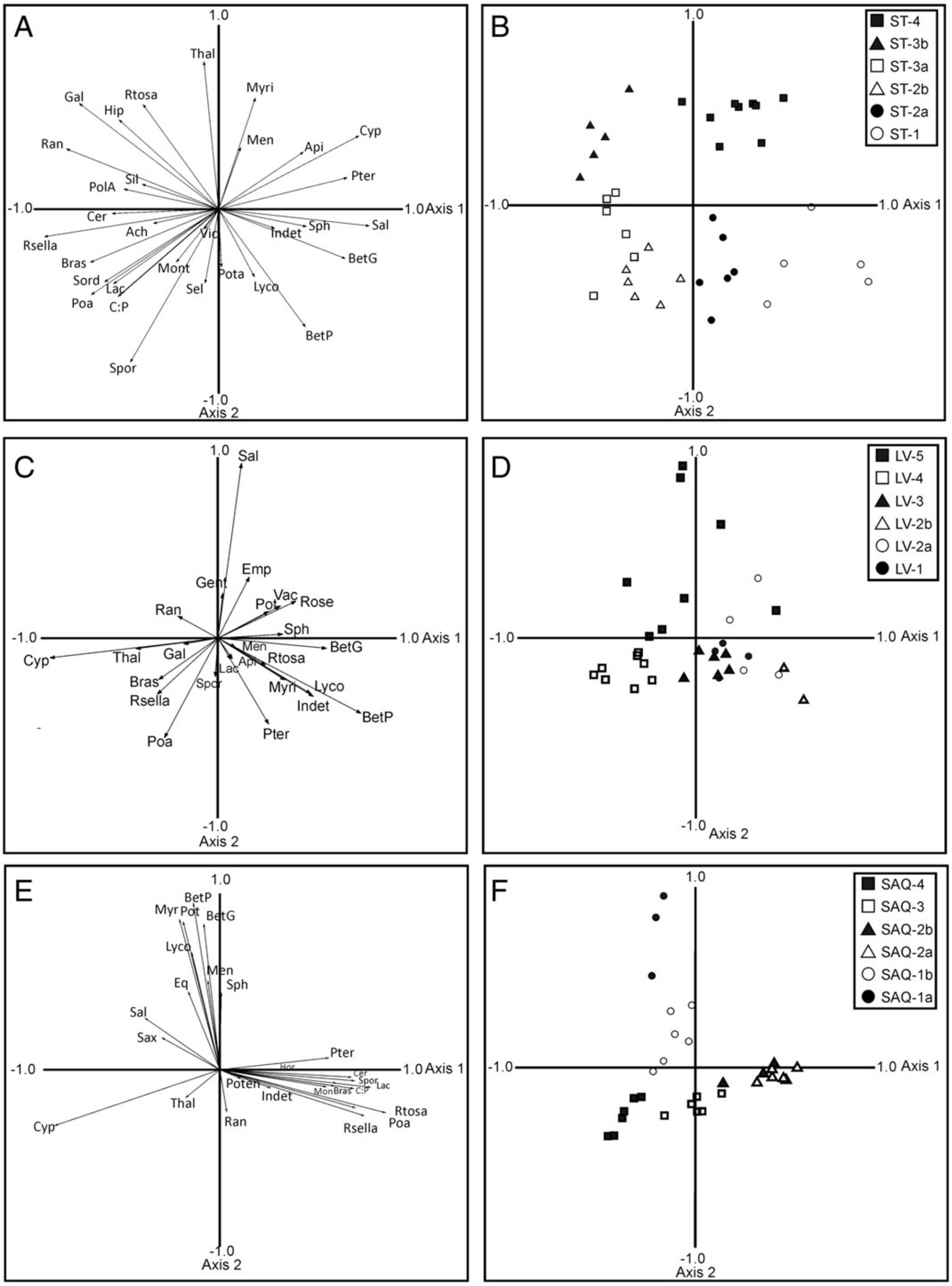

Figure 2. PCA plots of pollen for the three sites. (A) Pollen types and associated proxies from Saqqaata Tasia (selected taxa only). (B) Sample scores for the Saqqaata Tasia pollen and spore dataset. (C) Pollen types and associated proxies from Lake Vatnahverfi. (D) Sample scores for the Lake Vatnahverfi pollen and spore dataset. (E) Pollen types and associated proxies from Saqqaa. (F) Sample scores for the Saqqaa pollen and spore dataset. Key to abbreviations: Ach, *Achillea*-type; Api, Apiaceae; BetG, *Betula glandulosa*; BetP, *Betula pubescens*; Bras, Brassicaceae; Cer, *Cerastium*-type; C:P, Charcoal to pollen ratio; Cyp, Cyperaceae; Eq, *Equisetum*; Emp, *Empetrum nigrum*; Gal, *Galium*-type; Gent, Gentianaceae; Hor, *Hordeum*-type; Hip, *Hippuris vulgaris*; Indet, unknown and indeterminable; Lac, Lactuceae; Lyco, *Lycopodium annotinum*; Men, *Menyanthes*; Mont, *Montia fontana*; Myri, *Myriophyllum alterniflorum*; Poa, Poaceae; PolA, *Polygonum aviculare*; Pota, *Potamogeton*; Poten, *Potentilla*-type; Pter, Pteropsida (monolete) indet.; Ran, *Ranunculus acris*-type; Rose, Rosaceae; Rsella, *Rumex acetosella*; Rtosa, *Rumex acetosa*; Sal, *Salix*; Sel, *Selaginella selaginoides*; Sil, *Silene dioica*-type; Sord, HdV-55a *Sordaria*-type; Sph, *Sphagnum*; Spor, HdV-113, *Sporormiella*-type; Thal, *Thalictrum alpinum*; Vac, *Vaccinium*-type; Vic, *Vicia*-type.

Results and discussion

Saqqaata Tasia — regional site

Lithology

The analysed sequence from Saqqaata Tasia is broadly homogenous and comprises dark brown gyttja indicating a lacustrine depositional environment. The gyttja extends to a depth of 90 cm and rests on a base of coarse sand (the sediment contact was proven with a gouge auger, although it was only possible to recover the top 74 cm of the sequence using the Russian sampler). Above 46 cm the gyttja becomes lighter brown and slightly sandier.

Chronology

Contiguous 1 cm sieving of the Saqqaata Tasia core identified sufficient plant macrofossil remains for radiocarbon dating at three levels

Table 1
Radiocarbon dates from the three profiles.

Site	Depth (cm)	Lab code	Material	^{14}C yr BP (±1σ)	Cal BC/AD (±2σ)	δ^{13}C (‰)
Saqqaata Tasia	43.2–43	SUERC-36595	*Betula* twig	190 ± 35	AD 1650–1950	−26.9
	54–52	SUERC-36591	*Vaccinium uliginosum* leaf fragments, *Stellaria media* seeds (×12), and a piece of charcoal	730 ± 35	AD 1220–1380	−28.8
	58–56	SUERC-36590	*Vaccinium uliginosum* twig and leaf fragments, plus *Stellaria media* seeds (×10)	705 ± 35	AD 1250–1390	−28.1
Lake Vatnahverfi	42–41	SUERC-36600	*Betula* twig	405 ± 35	1430–1630	−28.1
	51–50	SUERC-12056	*Helodium blandowii* branches	585 ± 35	1300–1415	−23.0
	59.5–58	SUERC-36599	Bryophyte branches and leaves (cf. *Helodium blandowii*)	900 ± 35	1040–1215	−23.5
	68–65	SUERC-36598	*Carex* nutlets and bark fragments	1370 ± 35	600–695	−25.3
	75–73	SUERC-36597	*Carex* nutlets and bryophyte leaves and branches	1250 ± 35	675–870	−26.1
	81–80	SUERC-36596	*Carex* nutlets	1285 ± 35	655–810	−24.1
Saqqaa	27–26	SUERC-36589	Twig (cf. *Betula*), *Stellaria media* seeds (×12) and a piece of bark	865 ± 35	AD 1045–1260	−27.7
	33–32	SUERC-12049	*Calliergon cordifolium* branches, *Carex rostrata* nutlets (×4), *Carex* nutlets undiff. (×4), *Ranunculus* sect. *Batrychium* seeds (×2) and *Montia fontana* seed	1415 ± 35	AD 575–655	−21.7
	37–36	SUERC-36588	Bryophyte branches and leaves (cf. *Calliergon cordifolium*)	1670 ± 35	AD 255–525	−25.4
	44–43	SUERC-36587	Bryophyte branches and leaves (undiff.)	1325 ± 35	AD 650–770	−25.2
	50–49	SUERC-36586	*Carex* nutlets and utricles	2955 ± 35	1295–1050 BC	−22.7
	74–72	SUERC-12050	*Ranunculus* sect. *Batrychium* seeds (×31), *Carex rostrata* nutlets (×2), *Carex* nutlets undiff. (×5), *Hippuris vulgaris* seeds (×10), Poaceae seed, *Menyanthes trifoliata* seed, *Betula* fruits (×2), twig cf. *Betula*.	4165 ± 35	2880–2630 BC	−17.3

(Table 1; Fig. 3). Given this low density of age determinations *Clam* (Blaauw, 2010) was used to explore options for an age–depth model (Fig. 3). Smoothed splines either: (i) produced models with age–depth reversals at the top of the sequence (Figs. 3A, B), or (ii) bypassed the bulk of the probability distribution of the uppermost ^{14}C date (SUERC-36595) (Fig. 3C). Linear interpolation was also explored; however, this necessitated the treatment of the middle ^{14}C date (SUERC-36591) as an outlier in order to prevent age reversals (Fig. 3D). None of these approaches is deemed to have generated a robust age–depth relationship; consequently no age–depth model is adopted for this site. Ages in the interpretation of pollen-analytical data reflect the 2σ calendar ranges of the calibrated radiocarbon dates.

Numerical analyses

PCA (Figs. 2A, B) indicates reasonable separation of the data with the first two axes accounting for 34% and 23.3% of the respective variance. Axis 1 is characterised by strongly negative responses in pollen types that probably reflect Norse apophytes and introductions (*Cerastium*-type, Brassicaceae, Lactuceae, *Polygonum aviculare*, *Achillea*-type and *Rumex acetosella*). Positive scores for taxa typical of scrub and mire communities (*B. glandulosa*, *Salix*, Cyperaceae) suggest that axis 1 differentiates between natural and cultural vegetation communities. The environmental parameter represented by axis 2 is less clear but may reflect a gradient related to the nutrient status of the lake. Weak enrichment in the bottom half of the profile may be indicated by the negative score for *Montia fontana*, while positive values for less nutrient-demanding aquatics such as *Myriophyllum alterniflorum* and *Hippuris vulgaris* correspond with pollen samples in the upper section of the core.

Palynology

ST-1 (Fig. 4) opens with a basal sample that conceivably reflects the period immediately prior to *landnám*. Charcoal concentrations are low relative to the values recorded in the two subsequent LPAZs (and as such can probably be attributed to inputs from long distance transport), while pollen from Norse apophytes and introductions such as *R. acetosella* (cf. Schofield et al., 2013) is absent. There is no evidence of cultural activity and the wetland (mire surface) vegetation appears to be dominated by Cyperaceae, with *B. glandulosa*–*Salix* scrub and *B. pubescens* woodland dominating the dryland flora. High *M. alterniflorum* (c. 60%) undoubtedly points to an aquatic depositional environment.

Above the basal sample, the remainder of the LPAZ exhibits a pattern consistent with increasing human impact. Pollen from scrub and woodland declines in a steady manner and reaches a minimum of ~33% by the end of the zone. An increase in microscopic charcoal is suggestive of burning, while the first appearance of *R. acetosella* and a gradual expansion in Poaceae imply the expansion of grasslands and/or hayfields at the expense of scrub. The muted nature of these developments is consistent with the inferred large RSAP for this site and could reflect the arrival of settlers in the wider Vatnahverfi region.

The opening of LPAZ ST-2a reflects the local establishment of the farm at Ø71a. Poaceae rises along with total pollen concentration (Figs. 4, 5), perhaps indicating increased vegetation productivity, and there are expansions in Lactuceae, *Cerastium*-type and *Ranunculus acris*-type that imply the local establishment of hayfields (Schofield et al., 2007). There is also evidence for an increasing number of animals grazing close to the coring location. *Sporormiella*-type fungal spores rise to 3–6% and pollen types sensitive to grazing (such as Apiaceae) disappear, while other plants linked to grazing and disturbed ground (such as *Rumex acetosa*, *R. acetosella* and Brassicaceae) become established.

There is no evidence for increased landscape instability. Pteropsida (monolete) indet. spores – often associated with erosion – are erratic and display no clear relationship with LOI values. The latter continues to rise through the zone; a pattern that would appear to suggest increasing biological productivity within the lake (Levesque et al., 1993). Indeed, a peak in *H. vulgaris*, the flowering of which is promoted in nutrient-rich water (Fredskild, 1992), and weak decline in *M. alterniflorum* – typically associated with nutrient-poor lakes (Murray, 2002) – may point to a minor increase in nutrient supply as a result of Norse agricultural activities.

Sub-zone ST-2b is characterised by increasing Poaceae which probably indicates the intensification of farming and hay growing in the catchment. This is supported by an expansion of *R. acris*-type pollen (cf. meadow buttercups) and increases in *Sporormiella*-type, with rising *R. acetosella* implying a spread of grazed heaths. There is still no evidence of this leading to widespread landscape disturbance as LOI remains constant and the abundance of Pteropsida (monolete) indet. spores declines.

The opening of sub-zone ST-3a records a percentage and concentration fall in Poaceae pollen which may signify a decrease in the coverage of hayfields and grasslands, although a strong signature for anthropogenic activities remains. Charcoal concentrations are high and *Sporormiella*-type, albeit reduced, is still well represented. Pollen from

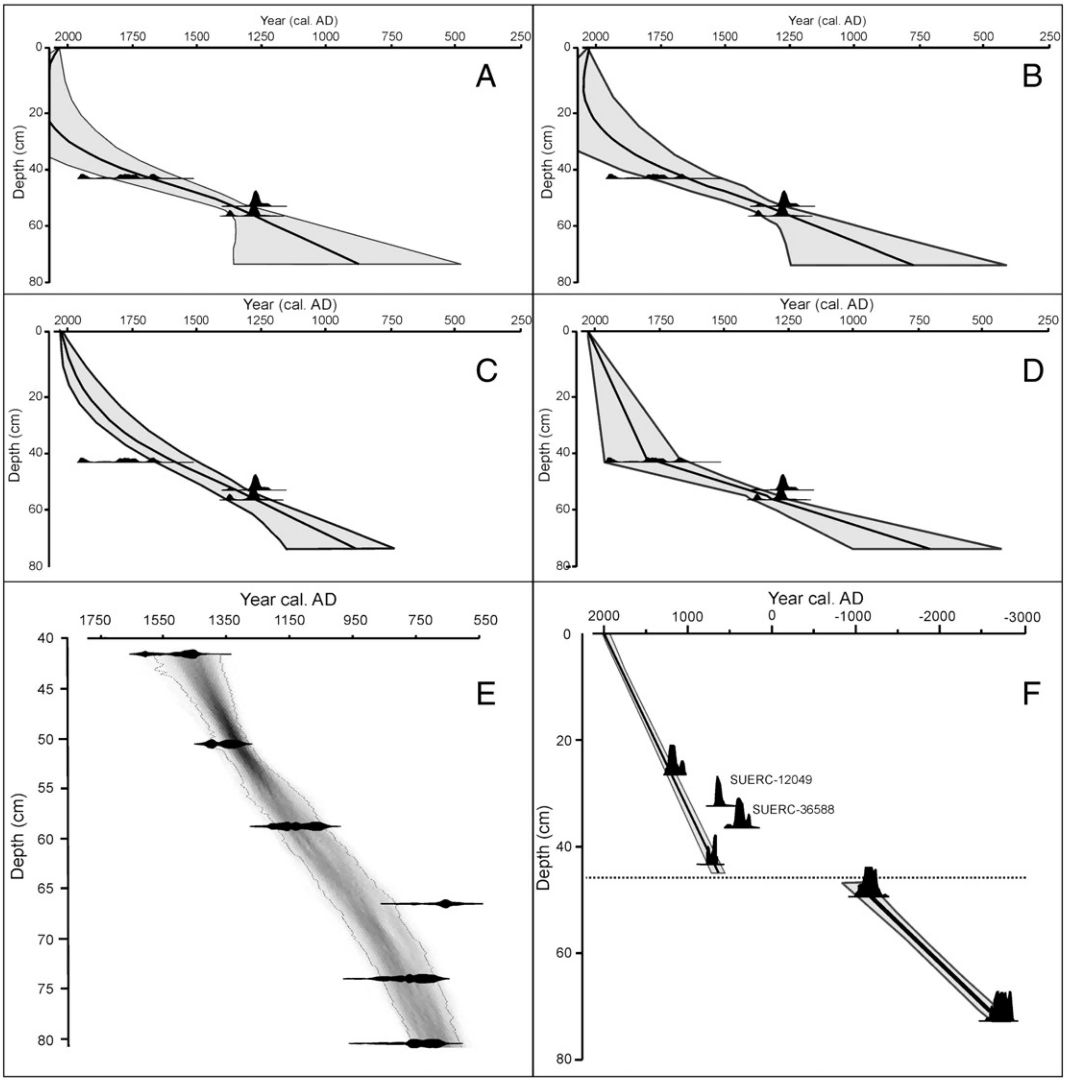

Figure 3. Age–depth model for the profiles investigated. (A–D) *Clam* scenarios for the Lake Saqqaata Tasia profile: (A) smoothed spline with smoothing of 0.3; (B) smoothed spline with smoothing of 0.35; (C) smoothed spline with smoothing of 0.4; (D) linear interpolation with the date at 54–52 cm classified as an outlier. (E) Lake Vatnahverfi generated using *Bacon*. The mean accumulation was set to 15 yr cm^{-1} with memory strength and mean respectively set at 4 and 0.7. The shaded area in the model indicates all possible age–depth models and the dotted lines show the 2σ age range; darker areas indicate increased certainty. (F) Saqqaa generated using *Clam*. Dates at 33–32 cm (SUERC-12049) and 37–36 cm (SUERC-36588) were classified as outliers and linear interpolation used to produce the model.

apophytes such as *P. aviculare* and *Achillea millefolium* becomes more common and there is a further increase in *R. acetosella*. These expansions may imply an increased intensity of grazing and perhaps soil erosion as intimated by a mid-zone decline in LOI and a rise in indeterminable pollen grains. It is possible that reduced Poaceae counts and concentrations are related to the suppression of flowering of grasses as a consequence of grazing (cf. Whittington and Edwards, 1993). Alternatively, it may reflect climatic cooling. The opening of ST-3a dates to cal AD 1250–1390 (SUERC-36590) — a period during which there is evidence for declining temperatures in the Greenland ice cores (Vinther et al., 2010) and potentially marking the beginning of the LIA. Indeed, a sharp reduction in *B. pubescens* – the flowering of which is temperature-sensitive (Hicks, 2001) – from a peak of c. 15% TLP in ST-2b to c. 8% by the end of ST-3a may be evidence of climatic deterioration.

In ST-3b woodland and scrub pollen continues to decline sharply, although in part this appears to be a proportional effect related to a rise in *Galium*-type. Nevertheless, concentration data (Fig. 5) do reveal further decreases in *B. pubescens* and *B. glandulosa*. Evidence for human impact also begins to decline; falling Poaceae pollen suggests further contraction of hayfields, and there are decreased counts of pollen from apophytes such as *R. acetosella* (3–4%) and the coprophilous fungi *Sporormiella*-type. Microscopic charcoal is also much reduced — a development which suggests that ST-3b reflects the terminal phase of activity at Ø71a.

The opening of ST-4 post-dates cal AD 1250–1390 and is marked by changes interpreted as reflecting climate deterioration and abandonment of the farm at Ø71a, or the wider Vatnahverfi region. A sustained fall in LOI values, from c. 25% to a minimum of 7% may provide evidence for declining temperatures. LOI may serve as a coarse proxy for biological productivity, and hence warmth (cf. Levesque et al., 1993; Kaplan et al., 2002), although it must be stressed that other factors, such as fouling by large concentrations of wildfowl (e.g. Stewart et al., 2013), have been demonstrated to influence productivity in arctic lakes. Nevertheless, in this instance declining pollen concentrations, indicative of reduced vegetation productivity, suggest that cooling is more likely. Microscopic charcoal falls to pre-*landnám* levels and the near-disappearance of *Sporormiella*-type suggests the absence of domesticated herbivores. Changes in other taxa are somewhat muted. Percentage data point to a slight but consistent decline in Poaceae and an expansion in Cyperaceae from c. 20% to 40%. This implies the gradual colonisation

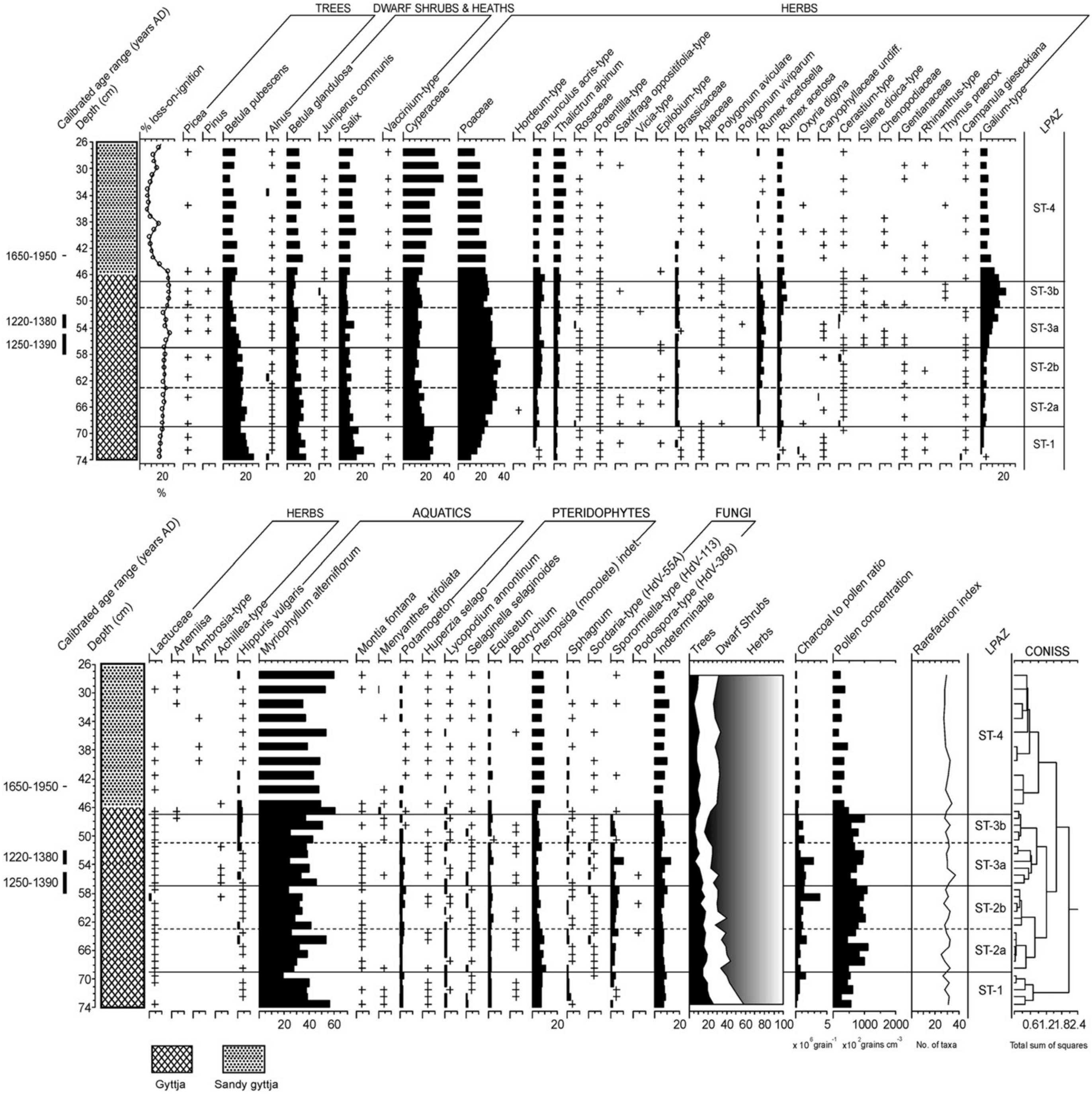

Figure 4. Percentage pollen and spore diagram for Saqqaata Tasia displaying selected taxa (minimum sum = 500 TLP). Also shown are the calibrated ^{14}C dates (2σ range), lithology, loss-on-ignition, microscopic charcoal, total pollen concentration and the rarefaction index. + indicates <1% TLP.

of former hayfield areas with sub-arctic steppe or the spread of mire. The recovery of woodland, scrub and dwarf-shrub heath taxa such as *B. pubescens*, *B. glandulosa* and *Salix* is not particularly marked and the peak sum of these taxa (c. 26%) in ST-4 is well below the pre-*landnám* value of 58%.

Lake Vatnahverfi — the outfield

Lithology

The sampled sequence comprises humified peat from 80 to 67 cm where it grades into fibrous peat. At 49 cm there is a further gradual lithological change to silty sandy peat.

Chronology

Six radiocarbon dates were obtained on plant macrofossils (Table 1). An initial inspection of the dates showed an inversion with the analysis at 68–65 cm (SUERC-36598; 1370 ± 35) returning an older radiocarbon age than the (stratigraphically lower) date at 75–73 cm (SUERC-36597; 1250 ± 35). Following calibration, there is a small overlap (c. 20 cal yr) in the age ranges for these dates. Modelling of the age–depth relationship was undertaken with *Bacon* (Fig. 3E) and subsequent calendar dates reflect the 2σ age ranges suggested by the age–depth model.

Numerical analysis

PCA (Fig. 2) indicates reasonable separation of the data with axes 1 and 2 accounting for 63.6% of the variance in the dataset. Axis 1 appears

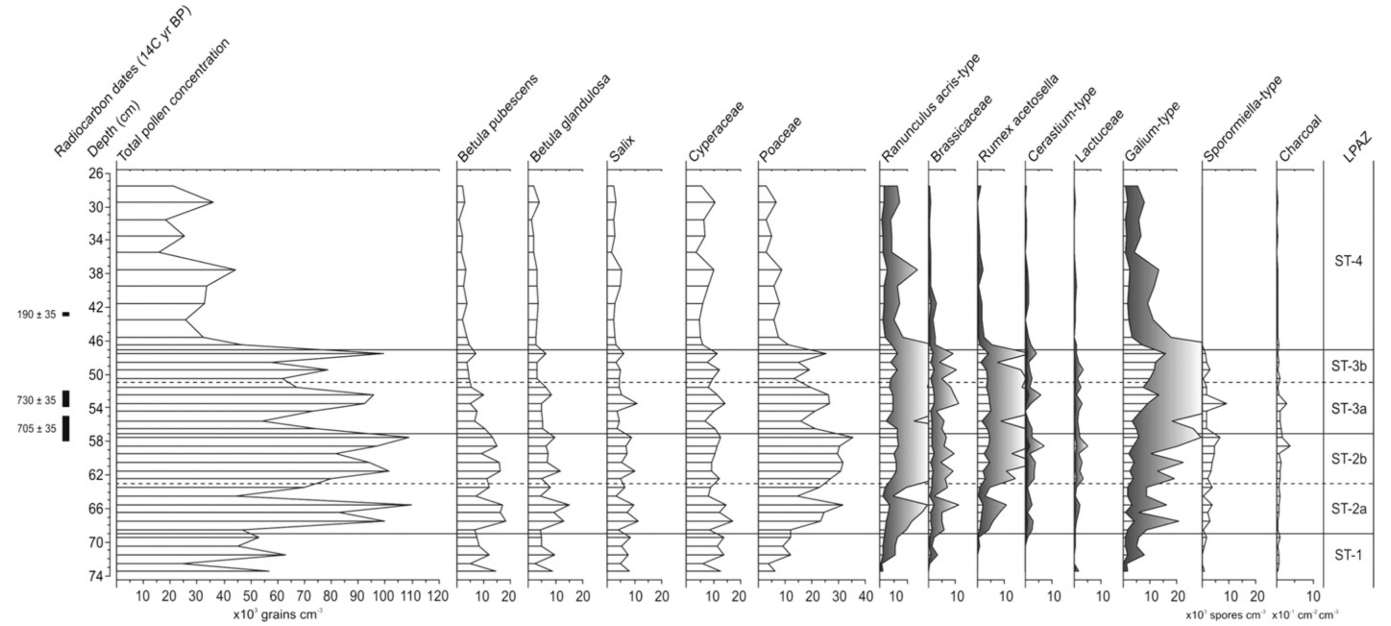

Figure 5. Pollen concentration diagram for Saqqaata Tasia showing total pollen concentration, selected pollen types, *Sporormiella*-type and microscopic charcoal (exaggeration curves where present are ×5). Calibrated radiocarbon dates are also displayed.

to reflect a gradient related to the openness of the landscape. Woodland, scrub and heathland taxa respond positively and types more reflective of an open landscape (Cyperaceae and Poaceae) are negative. Axis 2 may be related to grazing by wild or domesticated herbivores. *Sporormiella*-type responds negatively along this axis and, to a lesser extent, so do taxa that are sensitive to grazing such as Brassicaceae, *R. acetosella*, Lactuceae and Poaceae.

Palynology

The analysed sequence (Fig. 6) opens cal AD 600–760 and is dominated by Cyperaceae pollen (c. 25–35%) which is probably largely derived from sedges growing on the mire surface and around the lake margin. LOI is initially low, but rises through the zone, coeval with the emergence of spores from *Sphagnum* and herbaceous pollen types such as *Potentilla*-type and Rosaceae. This may reflect expansion of the mire around the lake and the local presence of *Potentilla palustris*. Beyond the mire the landscape appears to have been dominated by *B. pubescens* woodland, and *B. glandulosa*–*S. glauca* scrub and dwarf-shrub heath (c. 45–50%). Pollen and spores from plants common amongst scrub, such as *Thalictrum alpinum* and *Lycopodium annotinum*, accord with these observations. There is also a consistent trace presence of *R. acetosa* — this is unusual as it is commonly accepted to be a Norse introduction (Fredskild, 1973) or at least to expand in the presence of human activity (Schofield et al., 2013). Interestingly, *R. acetosa* was also identified before the Norse arrival elsewhere in Vatnahverfi (Ledger et al., 2013) and it may be the case that these rare occurrences reflect the local presence of low numbers of the plant prior to *landnám*. Poaceae counts are low, but occurrences of herbs such as Caryophyllaceae and *Campanula gieseckiana* may indicate the presence of grassland and herb-slope communities (Böcher et al., 1968).

Minor changes separate LPAZ LV-1 from LV-2a (beginning cal AD 690–870), which appear to reflect localised vegetation changes. Cyperaceae rises from 25% to 40% at the LV-1/2a boundary and there is a sharp fall in both *Sphagnum* (c. 25% to 5%) and *Potentilla*-type. This is concurrent with a general decline in LOI from c. 50% to 30%, demonstrating an increasing sediment flux into the basin. Poaceae increases marginally, as does the rarefaction index, linked to the emergence of pollen records for herbs such as Brassicaceae and Apiaceae which reflect the expansion of herb-slope and grassland communities. Woodland (c. 20–25%) and scrub (c. 20–25%) remain widespread, although there is a minor decline in *Salix*.

An increase in microscopic charcoal and the first appearance of *R. acetosella* attests to the arrival of Norse settlers at the opening of LV-2b (cal AD 830–1030). Cyperaceae declines and there is a slight rise in Poaceae to c. 20% TLP; patterns which are also reflected in the pollen influx data (Fig. 7). Such developments are common at *landnám* (e.g. Edwards et al., 2008) and may reflect hayfield establishment at nearby farms in the valley, or the more local expansion of grasslands.

The base of LPAZ LV-3 dates to cal AD 890–1075. Pollen assemblages in this zone continue to be dominated by Cyperaceae. Marginally elevated microscopic charcoal values appear to confirm the presence of settlers in the wider landscape, and an expansion of grazing is suggested by an increase in *Sporormiella*-type which peaks at c. 35%. Rises in Brassicaceae and *R. acetosella* coupled with a mid-zone decline in LOI may reflect the local impacts of grazing, although the significance of LOI changes is uncertain given the variability this exhibits prior to *landnám*. A continued increase in Poaceae points to the establishment of further farms in the valley or a modest expansion of local grassland/pasture. The latter appears more likely, probably at the expense of a woodland, scrub and dwarf-shrub heath.

LPAZ LV-4 opens cal AD 1050–1215 and displays mixed evidence for human activity. Microscopic charcoal remains slightly enhanced, but evidence for hayfields or pasture, which must undoubtedly be present in the wider landscape at this time, is inconclusive. Poaceae percentages hint at such as possibility, but influx remains low showing no increase over the pre-*landnám* baseline. Furthermore, the rarefaction index declines from 22 to 15, pointing to decreased species diversity, contrary to what may be expected of a cultural landscape (cf. Birks and Line, 1992). The only hints of pollen types indicative of hayfields or grassland pasture are rare occurrences of *Cerastium*-type and *Rhinanthus*-type, although the former may include pollen from species (e.g. *Cerastium arvense*) that grow amongst the scrub (Böcher et al., 1968).

Evidence for Norse farming activity is therefore muted and limited to elevated *Sporormiella*-type percentages of c. 2–3% and (initially) high frequencies of *R. acetosella*. Low percentages and influx of *B. pubescens* and *B. glandulosa* (Figs. 6, 7) suggest the continued exploitation of woodland and scrub, and declining *Salix* perhaps implies an intensification of this process. In this case, the increased presence of *Cerastium*-

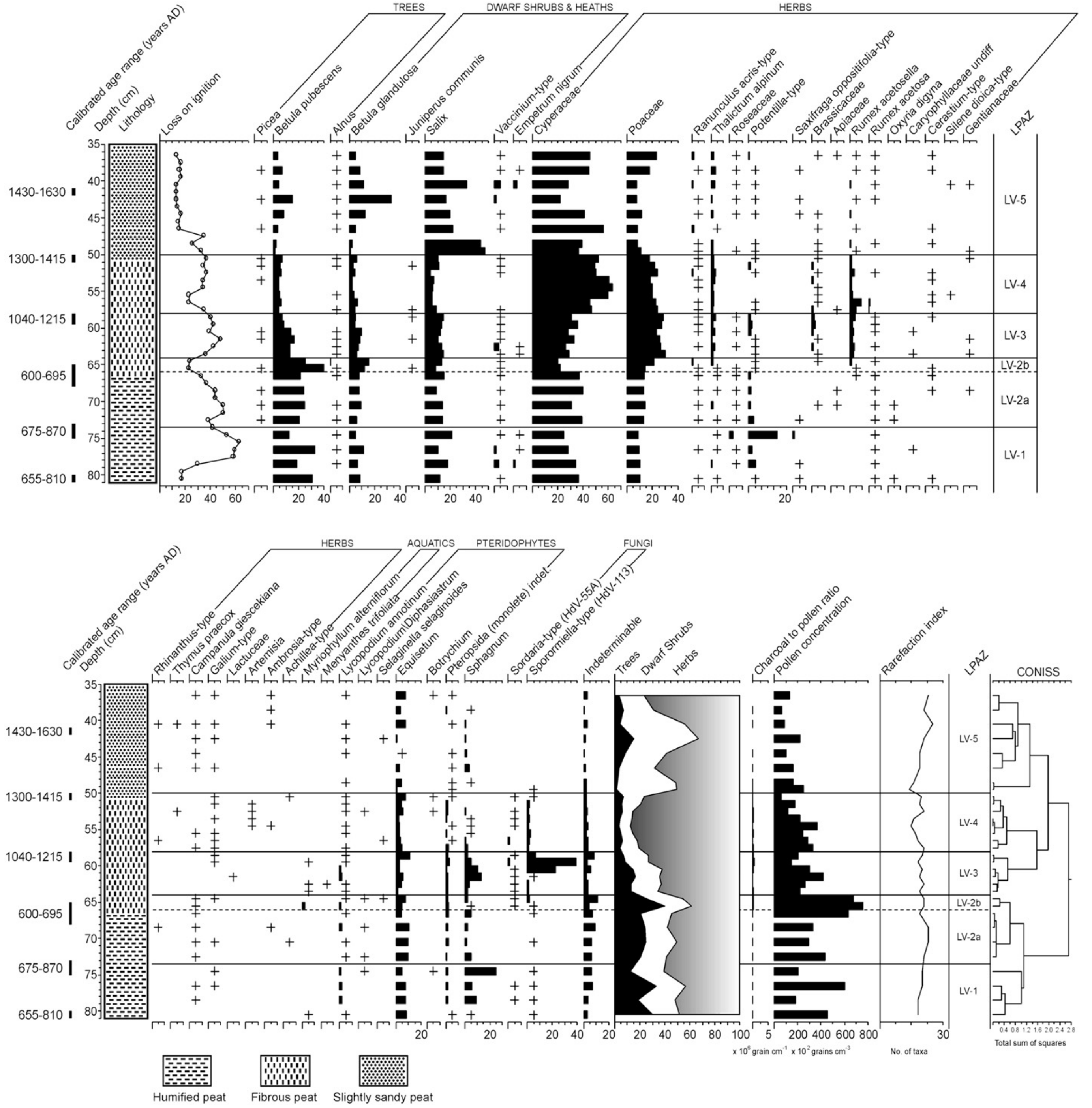

Figure 6. Percentage pollen and spore diagram for Lake Vatnahverfi displaying selected taxa (minimum sum = 500 TLP). Also shown are the calibrated ^{14}C dates, lithology, loss-on-ignition, microscopic charcoal, total pollen concentrations and the rarefaction index. + indicates <1% TLP.

type could reflect *Stellaria media* growing across areas of broken or disturbed ground (cf. Fredskild, 1978).

The LV-4/5 boundary (cal AD 1285–1400) records a sharp change in the pollen spectra, with a major increase in *Salix* percentages (rising from c. 10% to 45% TLP) and influx (climbing from c. 70 to 1370 grains cm^{-2} yr^{-1}). There is also increased influx of Cyperaceae pollen from c. 375 to c. 1060 grains cm^{-2} yr^{-1}. Evidence for human activity declines as Poaceae falls to pre-*landnám* levels and *R. acetosella* decreases. In addition, microscopic charcoal influx is much reduced and *Sordaria*-type and *Sporormiella*-type disappear, suggesting the abandonment of the area by both animals and people (cf. Schofield and Edwards, 2011; Edwards et al., 2011b).

Saqqaa — the infield

Lithology

The stratigraphy of the core from Saqqaa can be divided into a lacustrine (standing water) and a terrestrial (mire) phase. From the base the lithology comprises sandy gyttja until a sharp change at 45 cm where it becomes a brown moderately humified peat containing sand and silt.

Chronology

The radiocarbon dates from Saqqaa do not present a conformable sequence (Table 1; Fig. 3). The pollen spectra (Fig. 8) from 33 to 32 cm

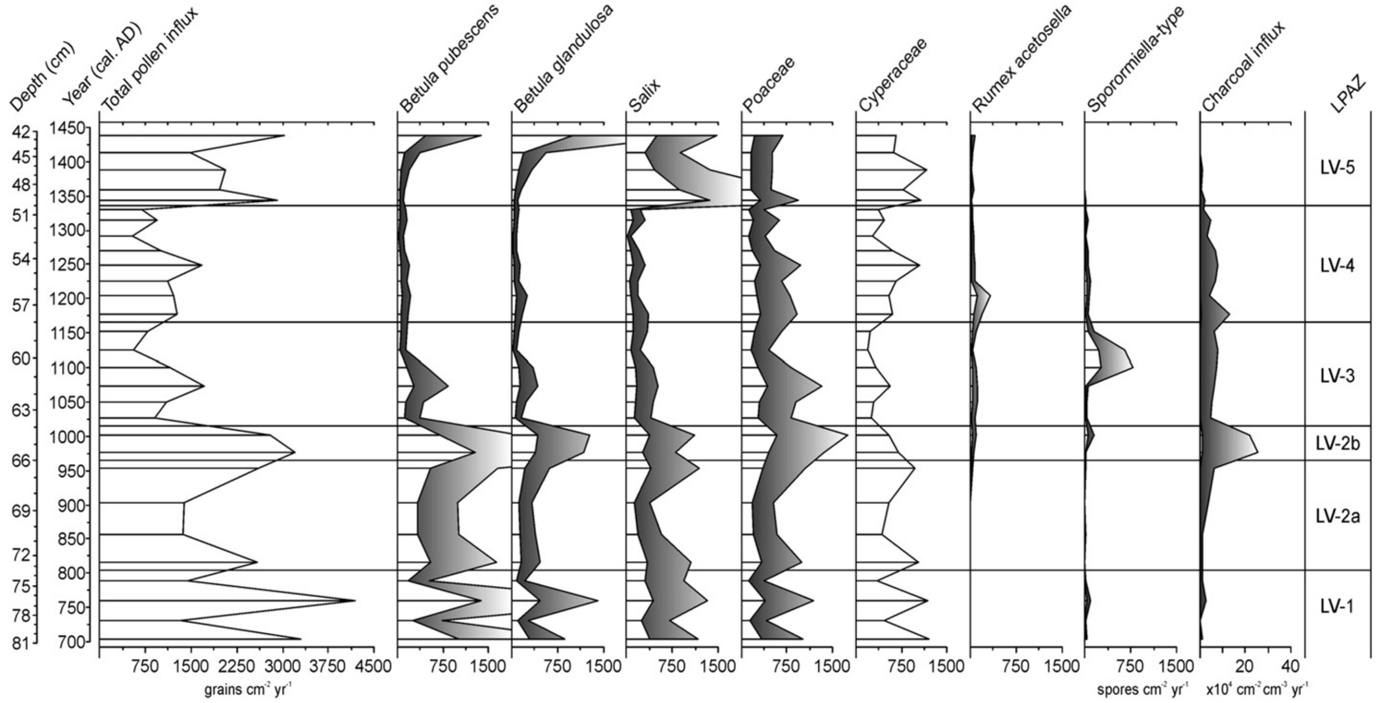

Figure 7. Influx diagram for Lake Vatnahverfi showing total pollen influx, selected pollen types, *Sporormiella*-type and microscopic charcoal plotted against the maximum a posterior probability (MAP) from the *Bacon* model (exaggeration curves where present are ×3, except for microscopic charcoal which is ×20).

record the presence of the Norse introduction *R. acetosella*, suggesting that SUERC-12049 (cal AD 575–655) is c. 400 ^{14}C yr too old. The material dated in this sample contained seeds from *Ranunculus* sect *Batrychium* – probably reflecting the aquatic plant *Ranunculus confervoides* (Böcher et al., 1968) – and *M. fontana* – a plant that grows in wet locations – raising the possibility of a 'reservoir effect' (sensu Abbott and Stafford, 1996). In this instance, 'old', ^{14}C-depleted, particulate organic matter may have been eroded from the catchment and re-deposited into pools on the mire. Decomposition of this material, through the processes of photodecay and heterotrophic respiration, may then have released this 'old' carbon into the water for uptake by aquatic plants, resulting in an aged sample. Such a mechanism could account for the apparent discrepancy here, and has been mooted for aquatic macrofossils elsewhere in southern Greenland (e.g. Edwards et al., 2011b; Massa et al., 2012). A similar argument can be made for the date at 37–36 cm (SUERC-36588; 1670 ± 35; cal AD 255–525), which also appears to be too old. The material dated for SUERC-36588 (cf. *Calliergon cordifolium*) is a moss which frequently grows submerged in water (Smith, 1978); this would also allow the uptake of ^{14}C-depleted CO_2.

Consequently SUERC-36588 and SUERC-12049 are classified as outliers and a hiatus is also placed at 45 cm on the basis of lithological change from gyttja to sandy peat and sharp changes in the pollen spectra (discussed below). A linear regression was fitted to the radiocarbon dates using *Clam* (Fig. 3F). This approach was considered the most appropriate given the limited number of reliable age estimates available from the core.

Numerical analyses

PCA indicated good separation of the data with the primary and secondary axes respectively accounting for 54.1% and 21.4% of the variability (Fig. 2). Axis 1 appears to indicate a gradient related to human impact, as introductions such as *R. acetosella* and *P. aviculare* respond positively, as do apophytes such as *M. fontana*, Lactuceae and *Cerastium*-type, and the coprophilous fungi *Sporormiella*-type and *Sordaria*-type. Axis 2 may reflect a gradient of landscape openness. Woodland and scrub pollen types such as *B. pubescens* and *B. glandulosa* both display positive values, whereas Poaceae and Cyperaceae (taxa typical of more open landscapes) show negative scores.

Palynology

SAQ-1a (Fig. 8) begins cal BC 1320–1090 and continues until cal BC 1075–795. Pollen from aquatic plants implies permanent standing water, e.g. a pool or small lake, as does lithological and macrofossil evidence — gyttja containing *H. vulgaris* and *Potamogeton* seeds. The terrestrial pollen assemblage is dominated by Cyperaceae and arboreal pollen such as *B. pubescens*, *B. glandulosa* and *Salix* suggesting reasonably dense coverage of woodland and/or scrub. Poaceae frequencies are low, as are those of herbs typically associated with grasslands and herb-slopes (e.g. *Campanula gieseckiana*).

The opening of LPAZ SAQ-1b reflects a clear change in the depositional environment indicating a hiatus or hydroseral succession. *M. alterniflorum* declines, *Potamogeton* becomes rare and changes in *B. pubescens*, *Salix*, Cyperaceae and Poaceae are marked. Increased representation of *Salix* may imply rising input from *Salix arctophila* and gradual succession from pool to mire, but a decline in Cyperaceae does little to support this argument. A depositional hiatus appears more likely, on the basis of an acute change in the stratigraphy from gyttja to moderately humified fibrous peat, and the sharp nature of the biostratigraphic changes.

Assuming a hiatus, the opening of LPAZ SAQ-1b and recommencement of sedimentation at Saqqaa are tentatively dated to cal AD 600–740 with pollen assemblages indicating an environment similar to SAQ-1a. Much of the Cyperaceae pollen is likely to come from the local wetland environment. Woodland, scrub and dwarf-shrub heath (c. 45% TLP) remains well represented. Rising Poaceae frequencies combined with rare occurrences of apophytic pollen types such as Brassicaceae, *Cerastium*-type, *Rhinanthus*-type and *R. acetosa* indicate increased coverage of grasslands. This pattern compares favourably with vegetation changes that might be anticipated to accompany the arrival of Norse settlers. Declining LOI, *Salix* and *B. pubescens* towards the end of the zone are also suggestive of *landnám* (Fredskild, 1973; Edwards et al., 2011a), yet the generally stable influx signal (Fig. 9) shows no real change in the abundance of *Salix* or

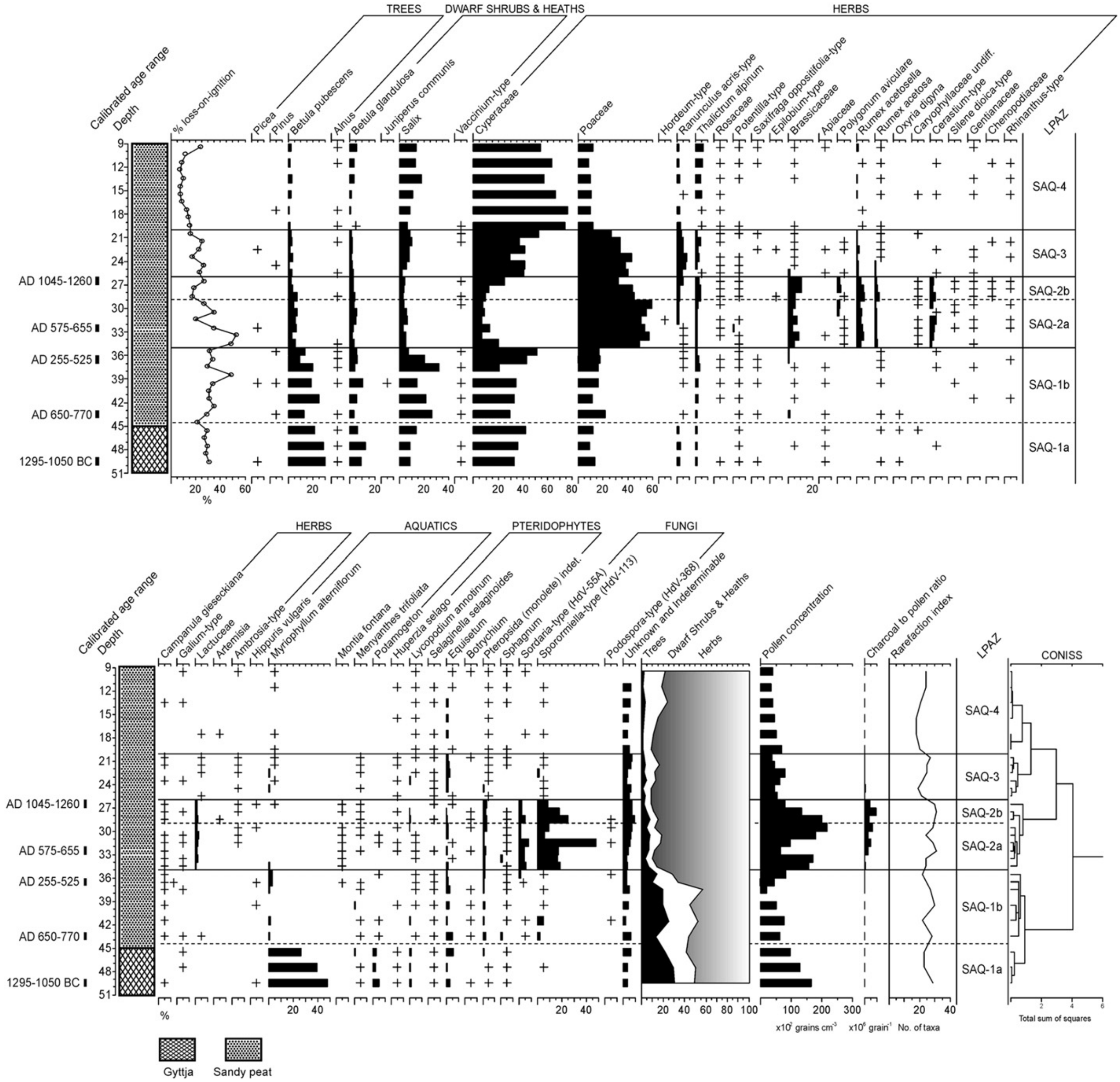

Figure 8. Percentage pollen and spore diagram for Saqqaa displaying selected taxa (minimum sum = 500 TLP). Also shown are the calibrated ^{14}C dates, lithology, loss-on-ignition, microscopic charcoal, total pollen concentration and the rarefaction index. + indicates <1% TLP.

B. pubescens. Indeed, microscopic charcoal, a characteristic feature of *landnám* (Edwards et al., 2011b) is absent, suggesting that the increase in the grazing indicators *Sordaria*-type and *Sporormiella*-type, together with aforementioned developments are related to wild herbivore grazing (cf. Ledger et al., 2013).

The opening of LPAZ SAQ-2a, dating to cal AD 880–1000, is characterised by a sharp increase in Poaceae and a decline in Cyperaceae that could be indicative of a further hiatus. Yet there is no lithological change at this depth, and developments in other taxa and pollen concentration (Fig. 8) are not especially marked. This suggests that the changes reflect *landnám*, with the rapid establishment of hayfields, which may be expected to produce such a signal in a small depositional basin intimately associated with an infield. Enhanced microscopic charcoal and the appearance of *R. acetosella*, *P. aviculare*, Brassicaceae and Lactuceae support this conclusion, as does a large increase in *Sporormiella*-type. Declining Cyperaceae percentages, and initially falling influx, point to a reduction in the area of wetland. *B. pubescens*, *B. glandulosa* and *Salix* percentages also decrease across the SAQ-1b/2a zone boundary, implying the clearance of woodland, scrub and dwarf-shrub heath, although influx data suggest a more modest decline.

LPAZ SAQ-2b opens c. cal AD 1070–1170 and records a sharp reduction in Poaceae pollen percentages and influx, indicative of falling productivity. Microscopic charcoal influx implies sustained burning probably associated with domestic activities, while declining *B. pubescens*, *B. glandulosa* and *Salix* influx imply continuity of scrub and woodland exploitation. An expansion of weedy taxa such as *R. acetosella*, *R. acetosa* and Brassicaceae and decline in LOI suggest intensifying erosion and an increase in disturbed and broken ground around the deposition site. Therefore it is possible that SAQ-2b records highly localised developments associated with the impoverishment of

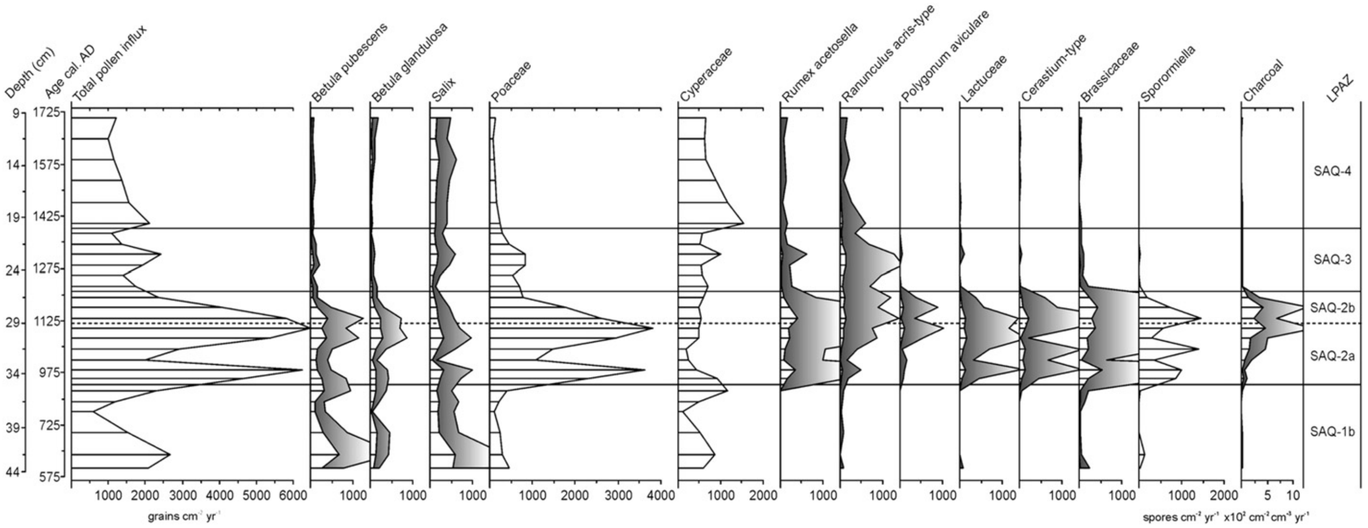

Figure 9. Influx diagram for Saqqaa showing total pollen influx, selected pollen types, *Sporormiella*-type and charcoal plotted against the median probable age from the *Clam* model (exaggeration curves where present are ×10 with the exception of *Betula pubescens*, *B. glandulosa*, *Salix* and microscopic charcoal, which are ×3).

the North Farm which is located c. 40 m east of the deposition site. Rising Cyperaceae counts may then reflect an invasion of hayfield areas around the North Farm.

The pollen-analytical changes in LPAZ SAQ-3 demonstrate continued human impact, but perhaps at reduced intensity. *B. pubescens* and *B. glandulosa* pollen influx show continued exploitation of scrub resources and probable reduction in their coverage. Concurrently there is a slight increase in *Salix*, decreased *Sporormiella*-type and falling charcoal influx, implying reduced human impact and some regeneration of willow scrub. Apophytes indicative of disturbed or broken ground such as *P. aviculare*, Brassicaceae, *R. acetosella* and Lactuceae become less abundant, as do pollen types associated with hayfields, such as *Cerastium*-type and *Rhinanthus*-type. Cyperaceae pollen increases to ~30–40% and there is a recovery in Poaceae to ~35–43%. The most likely explanation is that this evidence for declining human impact reflects the abandonment of the North Farm (cf. Vebæk, 1992). Evidence for continuity – such as rising Poaceae influx and the minor presence of apophytes – may imply a shift in farming focus and hayfields some 200 m west to an already, or recently established, South Farm. Edwards et al. (2008) proposed a similar argument at Ø2, Tasiusaq, where a distancing of activity from the sampling location was suggested to be the cause of a dampened signal for human impact. At Saqqaa, rising Cyperaceae and *Salix* counts could then reflect the colonisation of former hayfields associated with the North Farm.

Occupation of the site had apparently ceased at the beginning of SAQ-4, which begins cal AD 1350–1420. Indicators of human activity such as microscopic charcoal, although already much reduced, disappear completely, as do apophytes associated with disturbed ground. Similarly, *Sporormiella*-type becomes increasingly rare pointing to the removal of domesticated herbivores. Poaceae percentages fall sharply from c. 33% to 12%, reflecting a drop to pre-*landnám* levels, and there is a sharp rise in Cyperaceae to a maximum value of 80% TLP. These changes are consistent with patterns for abandonment elsewhere in the Eastern Settlement (cf. Fredskild, 1973; Edwards et al., 2011b) and clearly suggest the desertion of hayfields and the South Farm.

Synthesis

The pre-landnám landscape and arrival of Norse settlers

Prior to the arrival of the Norse, Vatnahverfi appears to have been a relatively wooded landscape compared to other locations in southern Greenland. At both Saqqaa and Lake Vatnahverfi woodland and scrub taxa (primarily *Betula* and *Salix*) account for c. 45–50% TLP with respective *B. pubescens* influx approaching 700 and 1350 grains $cm^{-2}\ yr^{-1}$, values which are suggestive of sparse to open woodland (Table 2; Hicks and Sunari, 2005). A single sample from Saqqaata Tasia covers the pre-*landnám* period and woodland and scrub there represents 58% TLP. Microscopic charcoal concentrations and influx are consistently low across all sites (Table 3) and provide a baseline against which the subsequent fire history of the region may be evaluated.

Alnus pollen comprises up to 1.4% TLP at Saqqaata Tasia and is consistently present throughout the pre-*landnám* period at Saqqaa and Lake Vatnahverfi. The modern distribution of *Alnus crispa* – the only species of alder native to Greenland – is ~61–67°N (Laegaard, 1971; Feilberg, 1984; Fredskild, 1996), placing it outside the boundaries of the Eastern Settlement. Therefore *Alnus* pollen found in peat sequences from southern Greenland is typically attributed to extra-regional sources (sensu Jannsen, 1973) arriving on the prevailing winds from North America (e.g. Fredskild, 1973). However, the shrub has been observed growing in Vatnahverfi near Igaliku Kujalleq (Fredskild, 1973) and *Alnus* sp. nutlets and roundwood charcoal have been reported from a Norse archaeological context at Timerliit (Bishop et al., 2013) c. 4 km northeast of Saqqaa. This combination of pollen and plant macrofossil evidence (especially *Alnus* nutlets, which must have grown on in situ shrubs) provides a strong argument that small numbers of the plant were growing within Vatnahverfi during the Norse period, and that (at least some of) the *Alnus* pollen recorded in diagrams from the Eastern Settlement may have been derived from sources inside the region.

The arrival of Norse settlers in Vatnahverfi is clearly documented at each of the locations analysed, although the intensity of impacts varies. For example, Saqqaata Tasia initially records muted evidence for human activity through a marginal increase in microscopic charcoal concentrations, a steady decline in woodland and scrub pollen, and a gradual increase in Poaceae. A general absence of pollen from apophytes, and only a limited increase in spores of coprophilous fungi (such as *Sordaria*-type and *Sporormiella*-type), suggests that these changes reflect the first arrival of settlers in the region establishing farms at other sites in the valley.

At the infield site of Saqqaa (Ø71), *landnám* is evident from cal AD 880 to 1000 as pollen from woodland and scrub vegetation is rapidly replaced by plant communities dominated by grasses and containing 'weeds', implying the creation of hayfields (Fig. 8). Microscopic charcoal influx (Fig. 9) is initially relatively low which suggests that burning played little role in landscape modification, contrary to arguments

Table 2
Betula pubescens pollen influx data and the postulated abundance of *Betula* woodland at Saqqaa and Lake Vatnahverfi for the pre-*landnám* and post-Norse periods.

Site	*Betula pubescens* influx (grains cm^{-2} yr^{-1})		Status of *Betula pubescens* according to the threshold values of Hicks and Sunari (2005)	
	Pre-*landnám*	Post-Norse	Pre-*landnám*	Post-Norse
Saqqaa (Ø71)	400–700	20–40	Sparsely present	Locally absent
Lake Vatnahverfi	350–1350	40–460	Occurring as open woodland	Locally absent to sparsely present

made for the Western Settlement (e.g. Iversen, 1934; Fredskild and Humle, 1991). Instead, high *Sporormiella*-type influx may point towards grazing herbivores (sheep and goats) having been deployed in the process of scrub and woodland clearance (cf. Edwards et al., 2008), although it is possible that in a small catchment, high *Sporormiella* may reflect the spread of manure (Graf and Chmura, 2006). Indeed, such an explanation may be more likely considering the initially contrary observation of increased LOI at *landnám*. Elsewhere in the Eastern Settlement, *landnám* is typically marked by declining LOI associated with trampling, grazing and the cutting of turves for building construction (Ledger et al., 2013). Therefore, it may be the case that increased LOI at *landnám* – for Saqqaa at least – is evidence of an initial attempt at soil improvement involving manuring and the incorporation of bedding and domestic debris spread across infield areas (cf. Golding et al., 2011) and the subsequent in-wash of some of these organic materials into the mire deposit.

Away from the farms, at Lake Vatnahverfi – in an area that the Norse would probably have considered the outfield – paleoecological evidence for *landnám* is more subdued. At cal AD 830–1030 a marginal increase in microscopic charcoal influx above background levels, a minor rise in *Sporormiella*-type and the first appearance of *R. acetosella* (Figs. 6, 7) are the only evidence for the arrival of Norse settlers. Contrary to the pattern from the infield, there is no decline in pollen from woodland and scrub. *B. pubescens* and *B. glandulosa* actually record increases in both percentage and influx terms, which may reflect a climatic signal of increasing warmth around AD 1000 (as observed in the DYE-3 $\delta^{18}O$ record [Fig. 10]), suggesting that the initial impacts of *landnám* were limited in the outfield region.

Differences in land use in the infield and outfield

The varying intensities of *landnám* are not the only noticeable difference between the paleoecological records from the infield and outfield locations. At Saqqaa, vegetation productivity is greatly increased during the Norse period, with total pollen influx at least double that of the pre-*landnám* period and twice that of the outfield (Fig. 10). The majority of this is related to a fourfold increase in Poaceae influx and a significant rise in pollen influx from ‘weeds’ such as *P. aviculare*, Lactuceae and *Cerastium*-type. This pattern is consistent with those observed elsewhere in Greenland (e.g. Schofield et al., 2008; Schofield and Edwards, 2011) and probably reflects the absence of grazing pressure in infield areas which would have been reserved for producing fodder for overwintering livestock. Similar patterns are evident in the concentration data from the more regional site of Saqqaata Tasia.

Table 3
Mean charcoal influx and concentration data for pre-*landnám*, Norse and post-Norse samples analysed in this study. Note that the time covered by each of the three periods, and the size of the datasets from which mean values are calculated, varies slightly according to the temporal length and sample resolution of the analysed records, and the timing of *landnám* and abandonment at individual sites (determined using the pollen records).

Site	Pre-*landnám*	Norse period	Post-Norse
Charcoal influx ($\times 10^2$ cm^{-2} cm^{-3} yr^{-1})			
Saqqaa (Ø71)	0.020	1.300	0.007
Lake Vatnahverfi	0.015	0.040	0.005
Charcoal concentrations (cm^2 cm^{-3})			
Saqqaata Tasia (Ø71a)	0.03	0.10	0.02

Contrary to patterns in the infield, total pollen influx declines through the Norse period at Lake Vatnahverfi. *B. pubescens* and *B. glandulosa* influx both decrease sharply, implying the clearance of woodland and scrub and an opening up of the landscape. A proportional increase in Poaceae to c. 28–30% suggests replacement with herbaceous plant communities, e.g. grassland pasture and hayfields. However, Poaceae influx data is not appreciably different to the pre-*landnám* values (Figs. 7, 10) suggesting there was no significant expansion in the grass cover. Rather, it implies that the apparent emergence of grassland communities is an artefact of proportional data and related to a relative decline in *Betula*.

This raises the question of what is causing the decline in *B. pubescens* and *B. glandulosa* influx if woody taxa are not being cleared? A possible explanation may be that *Betula* scrub and dwarf-shrub heath were being managed as woodland pasture. Grazing has been demonstrated to significantly suppress pollen production and release in grasslands (Groenman-van Waateringe, 1993; Whittington and Edwards, 1993) and would almost certainly have had the same effect in scrub and woodland. The practice of grazing sheep in birch scrub is known in Iceland (Buckland, 2000) and Ívar Bárdarsson's *Description of Greenland* alludes to the grazing of livestock in scrub (Krogh, 1967; Schofield and Edwards, 2011). Counts of *Sporormiella*-type (HdV-113), which register c. 2% TLP at the beginning of the zone and then rise to c. 35% towards its end, certainly point to the presence of grazing animals. *Sporormiella* influx peaks at c. 300 spores cm^{-2} yr^{-1} and is concurrent with the sharp decline in *B. pubescens* and *B. glandulosa* pollen. An alternative explanation could be that *Betula* was being coppiced for fuel, or as a fodder resource, a custom known from Norway (Austad, 1988) and Iceland (Buckland, 2000) and inferred for Greenland (Amorosi et al., 1998; Ross and Zutter, 2006). If a system of leaf and twig foddering was in place this would have resulted in these parts of the plant being removed prior to flowering, which results in suppressed pollen production and sometimes palynological invisibility of coppiced species (Edwards, 1993; Waller et al., 2012).

Palynological work undertaken at sites located away from Norse ruins has recorded more muted declines in scrub and woodland (see Fredskild, 1973, 1992). This may point to grazing and exploitation of the outfield areas being more intensive in Vatnahverfi, yet it is as probable that the taphonomy and source area of basins are the main factors in explaining these differences. Previous studies (e.g. Fredskild, 1973) located at distance from the ruins of Norse farms tend to be from larger basins which recruited a more regional pollen rain than Lake Vatnahverfi; as a result, they received a larger input of background pollen that suppressed more localised patterns (Davis, 2000).

Abandonment and the legacy of Norse settlement

The terminal date of Norse occupation in Greenland is traditionally placed around the mid 15th century AD. The data reported here do not contradict this, with abandonment indicated at Saqqaa around cal AD 1350–1420, at Lake Vatnahverfi cal AD 1290–1400, and at Saqqaata Tasia shortly after AD 1220–1380. These dates are in agreement with those from other paleoecological studies in the region that also point to abandonment from the mid-14th century (e.g. Edwards et al., 2011a; Massa et al., 2012; Ledger et al., 2013), although the existence of a radiocarbon calibration wiggle for the period ~cal AD 1340–1400 is unfortunate in this regard (Edwards et al., 2013). At each site the end of settlement is marked by a rise in Cyperaceae, which represents

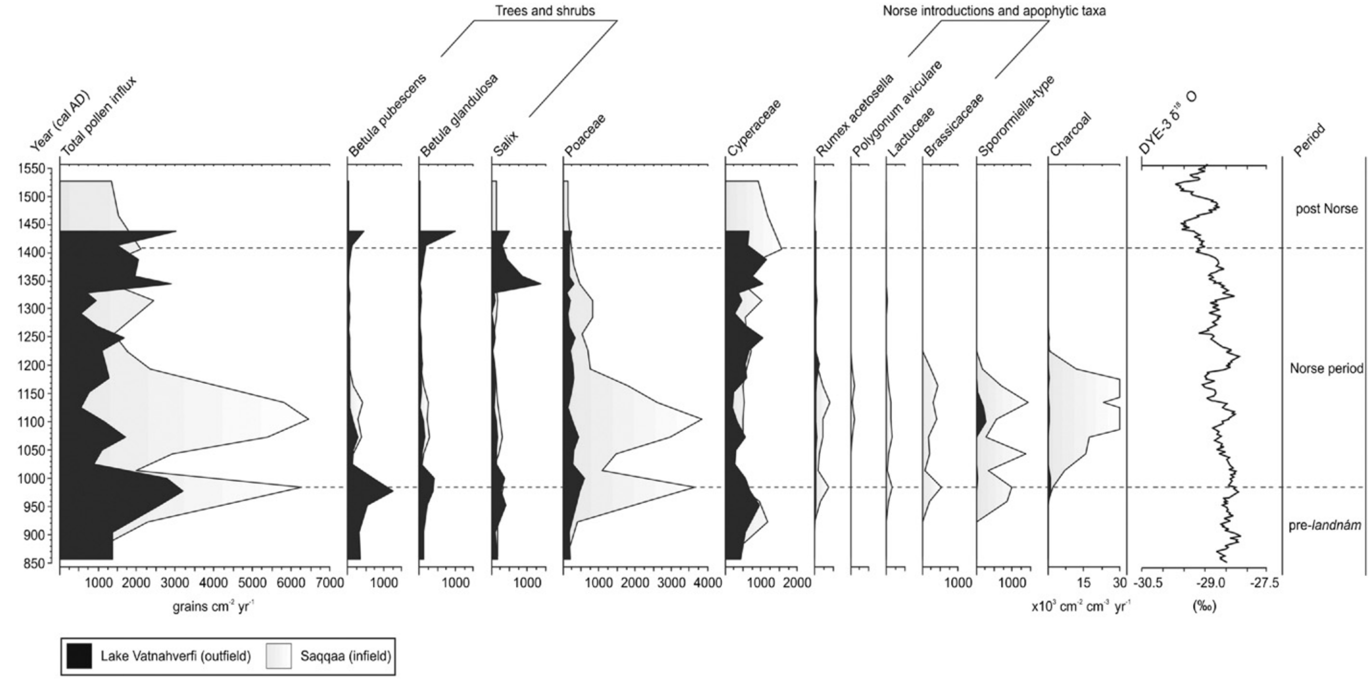

Figure 10. Pollen influx diagram comparing selected taxa in the outfield and infield locations. Data from Lake Vatnahverfi (black) has been 'stacked' over that from the infield location of Saqqaa (grey) to illustrate the differences between the two sites. Plotted alongside is the 20 year running average of winter δ^{18}O for the DYE-3 ice core (after Vinther et al., 2010). Decreasing δ^{18}O values (i.e. a shift to the left on the graph) indicate cooling.

an expansion in sub-arctic steppe (dryland), mire (wetland) communities, or both. The former appears more likely as there is no obvious evidence indicating a wetter climatic regime. In infield locations a sharp fall in vegetation productivity is characteristic, with Poaceae and ruderal taxa declining as hayfields fell into disuse. In the outfield around Lake Vatnahverfi, coprophilous fungi disappear from the assemblages and vegetation productivity (as measured by influx) doubles, seemingly in response to a release of grazing pressure. Microscopic charcoal concentrations and influx return to levels that are commensurate with those recorded prior to *landnám* (Table 3).

The clearest consequence of Norse settlement in Vatnahverfi is the widespread denudation of *B. pubescens* woodland and its failure to recover. Prior to *landnám*, *B. pubescens* accounted for c. 20–25% TLP, but in the immediate abandonment period values are reduced to just 2–10% (Figs. 4, 6 and 8). Indeed, pollen influx data, which prior to *landnám* suggested areas of open woodland (Table 2), indicate a probable near absence of *B. pubescens* within the vicinity of the sites studied following their abandonment (sensu Hicks and Sunari, 2005). Such a finding is not unexpected given the known impacts of Norse settlers on their local environment in Iceland (e.g. Erlendsson and Edwards, 2009; Erlendsson et al., 2009) and the general importance of wood resources to Norse societies (Church et al., 2007). In contrast, *Salix* percentages and influx are comparable to, and at Lake Vatnahverfi exceed, pre-*landnám* values. This may reflect less intensive exploitation of *S. glauca* scrub during the settlement period, though this seems unlikely. A more plausible explanation is that the cooler temperatures of the LIA – illustrated in the falling DYE-3 δ^{18}O values (Fig. 10) – suppressed the re-emergence of *B. pubescens*, a situation that the more cold-tolerant *S. glauca* (cf. Böcher et al., 1968) exploited.

Conclusions

Prior to this research, the paleoecological study of *landnám* in Greenland has provided either single site interpretations of landscape-scale impacts, or localised paleovegetational data from archaeological sites. The present study represents the first attempt to examine the intensity of the environmental impacts of Norse *landnám* at a variety of spatial scales across a small geographical area. At the landscape level, *landnám* in Vatnahverfi is characterised by removal of scrub and woodland, the creation of hayfields and an increase in microscopic charcoal. This pattern holds for localised reconstruction from the infield at Saqqaa, although here there is stronger representation of 'weeds' associated with agricultural activities and coprophilous fungi that perhaps reflect manuring of infield areas. In the outfield (Lake Vatnahverfi) there is little evidence for an expansion in grasslands, increases in microscopic charcoal are minor and likely derive from domestic activities around farming locales. This implies that wholesale burning of woodland and scrub to stimulate to development of grasslands did not occur. Rather, the Norse period is characterised by suppressed vegetational productivity that may reflect exploitation and/or the management of woodland and scrub through grazing and coppicing. As long recognised, such findings clearly demonstrate the value of multiple site reconstructions of different spatial scales and illustrate that the intensity of the paleoecological signal for Norse *landnám* is influenced not only by the depositional context, but also by proximity to archaeological activity (cf. Edwards, 1983, 1991a, 1991b). In applying such principles to the Vatnahverfi area, this study provides the first integrated paleoecological evidence for the differing landscape management practices of the Norse in Greenland.

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