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Pollen and non-pollen palynomorph evidence of medieval farming activities in southwestern Greenland

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Abstract Radiocarbon dating, pollen and non-pollen palynomorph analyses from a lake core were used to establish the timing and effects of farming activities around Lake Igaliku, Eastern Settlement, Greenland. The absence of agro-pastoral impact before the medieval colonization by Europeans provides an opportunity to understand the development of farming activity in a pristine landscape. The results show that the first phase of clearance and grazing pressure, without the expansion of the Norse apophyte (native plant, in habitats created by humans) *Rumex acetosa* type, could have occurred in the 9–10th century A.D. The presence of Norse settlers and livestock is clearly recorded from the 11–12th century A.D. with increasing frequencies of the Norse apophytes *Rumex acetosa* type and *Ranunculus acris* type, and coprophilous fungi. This colonization phase is followed by a period of decreasing human impact at the beginning of the 14th century, with a decrease in weeds, apophytes and coprophilous fungi suggesting a reduced grazing pressure. The regrowth of

Salix and *Betula* and the disappearance of anthropogenic indicators except *Rumex acetosa* type between the 15th and 18th century demonstrate the abandonment of the settlement, until the development of contemporary agriculture in the 20th century.

Keywords Non-pollen palynomorphs · Palynology · Grazing pressure · Greenland

Introduction

The Norse settlement of Greenland from A.D. 985 to ca. 1450 has been particularly studied by archaeologists and palaeoecologists with a particular interest in agro-pastoral practices (Arneborg 2005; Dugmore et al. 2005; Commisso and Nelson 2008; Buckland et al. 2009), demography (McGovern 1991; Lynnerup 1996) and the analysis of individual sites (Algreen-Møller and Madsen 2006; Gul-dager et al. 2002). According to historians, the Norse colonization began in A.D. 985 with Erikrur Rauðe Þorvaldsson (Erik the Red). It developed on the basis of an agro-pastoral economy and, at its height, supported a population ranging from 3,000 to 6,000 inhabitants (Lynnerup 1996; McGovern 1991). Farmers spread out over three parts of west Greenland with the two most important settlements situated at 60°N, *Østerbygden*, district of Narsaq, the so-called Eastern Settlement, and 64°N *Vesterbygden*, district of Nuuk, the so-called Western Settlement (Fig. 1). Farmers raised cattle, sheep, goats, horses, pigs and dogs, but they also hunted seal and caribou as well as fishing (Dugmore et al. 2005). In order to extend pastures and managed hay fields, they cleared the sparse arctic shrubs intensely (Fredskild 1992) and fertilized the grasslands with manure (Commisso and Nelson 2007, 2008; Ross and

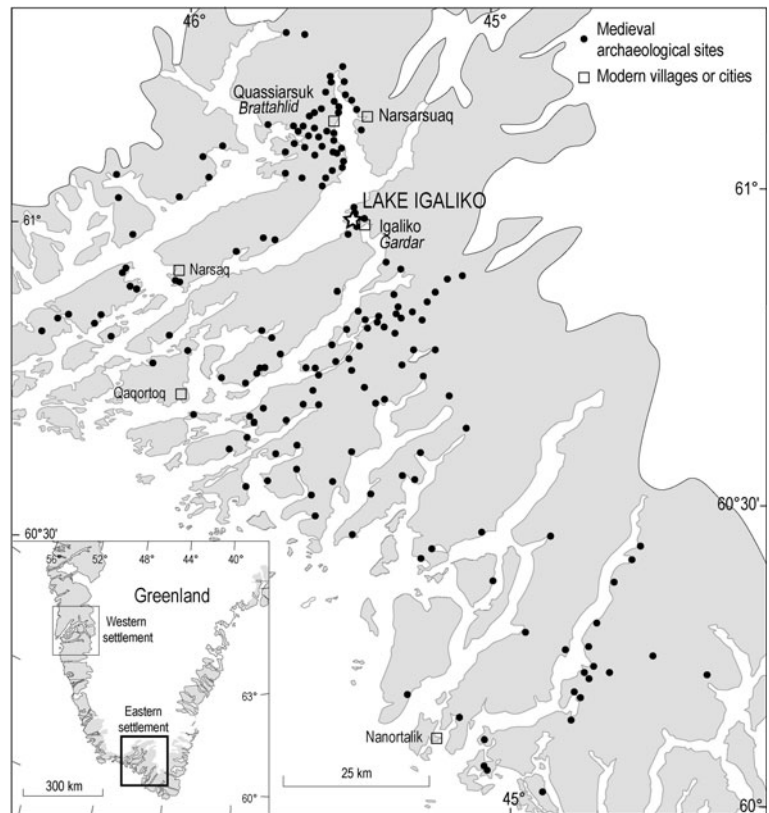
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Fig. 1 Map of the Norse Eastern Settlement in southwest Greenland (historical data according to Kuijpers et al. 1999)



Zutter 2007; Buckland et al. 2009) and practised irrigation (Arneborg 2005; Adderley and Simpson 2006).

The chronology of the abandonment of these colonies is unclear and the way in which it happened is still the subject of debate. The only point on which the authors agree is the role of the climatic change of the Little Ice Age (Dansgaard et al. 1975; Stuiver et al. 1995; Barlow et al. 1997) which isolated the community and caused a decline in agricultural yields (Barlow et al. 1997). In spite of a change in activity with more hunting and fishing (Arneborg et al. 1999, 2002), Norse society of south Greenland collapsed during the 15th century and all the farms were abandoned. It was not until the 18th century that the medieval Norse territories in the southwest of Greenland were partially reoccupied again by European migrants (Keller 1990), as well as in the 1920s for the redevelopment of agro-pastoral activities (Guldager et al. 2002), within the very centre of the former Norse agricultural areas.

The impact of Norse activities on the arctic environment, following the *landnám* or settlement, from Old Norse, “land-take”, is mainly shown by archaeobotanical analyses on archaeological sites or offsite in ponds and peat deposits but close to groups of ruins. Fredskild (1973, 1978, 1992) established a biochronology for the Holocene in Greenland and, more particularly, in the Eastern Settlement in the Qassiarsuk area, from two ponds and four peat-filled hollows. Fredskild’s investigations have

revealed the arrival of Norse farmers in the 10th century and their perceptible impact on the environment from scrub clearance, the creation of hay meadows and the introduction of non-indigenous taxa. Radiocarbon dates in Fredskild’s studies are few in number and sometime imprecise (1973, 1978; Sandgren and Fredskild 1991). In order to improve these first results and to provide high resolution palaeoecological data, Schofield et al. (2007a) and Edwards et al. (2008) have studied two other peat deposits in the same area, in Qorlortoq valley and Tassiusak. Pollen analyses show human impact from the 10th century, but the first millennium A.D. is poorly recorded in the studied sequences due to sedimentological hiatuses from peat cutting, or a low sediment accumulation rate. These recent investigations also attempted to provide a good chronology of the Norse occupation during the first half of the 2nd millennium A.D. Most recently, Buckland et al. (2009) have analysed drainage ditches containing clay-rich peat which were located close to the settlement ruins of *Gardar*, about 2 km from Igaliku. Pollen, insect analyses, as well as AMS radiocarbon dates on seeds revealed evidence for manuring and irrigation for the period of ca. A.D. 1110–1370.

In light of these previous studies mentioned above, and in order to overcome the difficulties encountered such as with the sedimentation rate and peat cutting, we investigated continuous palaeoenvironmental archives in mid-lake sediments from Igaliku, near the *Gardar* archaeological site.

This research aims to assess the transition between a pristine landscape and a cultural one, and is based on an approach using pollen and non-pollen palynomorph (NPPs) proxies and AMS radiocarbon dates of the sequence. NPPs are a great help in demonstrating the different phases of grazing pressure. Results from fossil assemblages are also compared with those found in samples of modern sheep and horse dung.

Materials and methods

Location and vegetation around Lake Igaliku

Igaliku, the Norse *Garðar*, is located at the head of the Igaliku Fjord and was at the centre of the Eastern Settlement (Fig. 1). The first settler of the area accompanied Erik the Red from Iceland (Buckland et al. 2009). Later, *Garðar* became the episcopal residence; the first bishop, Arnald, arrived in 1126 and had the largest medieval farms of Greenland, showing its economic importance and activity. At Igaliku, 52 Norse archaeological structures are recorded, including large byre-barn complexes, animal pens and enclosures, sheep/goat houses and an irrigation system for fodder production (Norlund 1929). The *Ping*, general assembly for Greenland, was located in *Garðar*. Lake Igaliku (informal name) is situated about 2 km northwest from *Garðar* and is easily accessible for farmers or livestock (Fig. 2).

Today, the north shore of the lake is overlooked by slopes where patches of *Salix glauca* (grey willow), *Betula*

glandulosa (dwarf birch) and *Juniperus communis* (juniper) grow (Fig. 2). The south shore is a managed agricultural landscape used for hay meadow. *Ranunculus acris*, *Rumex acetosa* and *Taraxacum officinale* grow around the farms and sheep graze in the entire area.

The deepest part of the lake was cored from a floating platform (61°00'24"N–45°26'30"W, 30 m a.s.l.). A sandy and silty Holocene sequence of 400 cm was sampled with a piston corer in June 2007 and the upper 65 cm were also cored with a gravity corer.

Modern sheep and horse dung samples were collected in July 2007 and September 2008. July samples were collected in pasture around Qassiarsuk and September samples were collected in pastures around a farm in Søndre Igaliku, south of Igaliku. We have chosen sheep and horse dung because they are nowadays the most common herbivores in southern Greenland. Cows are very rare; pigs, goats and reindeer are absent. The kind of livestock is not of great importance: most coprophilous fungi grow indiscriminately on any herbivore dung (Bell 2005).

Sediment samples and dung samples of 1 cm³ each were processed for pollen and non pollen palynomorph (NPP) analysis using standard techniques (Moore et al. 1991). They were treated with HCl (10%), NaOH (10%), HF (40%), ZnCl₂ and acetolysis (8 min). A minimum of 400 pollen grains of terrestrial plants was counted in each sample to ensure statistical significance. Cyperaceae, hygrophilous plants such as *Menyanthes trifoliata* and *Equisetum*, and aquatic taxa, exotic taxa, spores and non-pollen palynomorphs were excluded from the pollen sum.

Fig. 2 View of Lake Igaliku in southwest Greenland, with the coring location and farmed surroundings (photo towards the north, by V. Bichet 2007)



Pollen grains were identified with the aid of a reference collection of Greenlandic modern pollen types and keys (Fægri and Iversen 1989; Moore et al. 1991), photographs (Reille 1992; Beug 2004). In accordance with Fredskild (1973), *Betula* grains larger than 20 µm were assigned to *B. pubescens* and the remainder assigned to *B. glandulosa*. Pollen preservation was systematically recorded for each *Betula* grain encountered, in order to observe evidence of degradation. The pollen diagram was drawn using TILIA and TGView software (Grimm 1991). Pollen zones were delimited with the help of CONISS (Grimm 1987).

Non-pollen palynomorphs (Fig. 3) were identified according to Bell (1983), Jankovská and Komárek (2000), Turton and McAndrews (2006), van Geel (1978, 2001), van Geel et al. (2003) and van Geel and Aptroot (2006), and percentages were calculated on the basis of the same pollen sum used for the pollen diagram (van Geel et al. 1981).

Radiocarbon dating and age–depth model

The chronology of the sequence is established by accelerator mass spectrometry (AMS) ^{14}C measurements along the upper 125 cm of the core and completed by Caesium measurements for the most recent sediment (Table 1; Fig. 4). ^{137}Cs activity was measured on a 0.5 cm thick sample in the upper 10 cm.

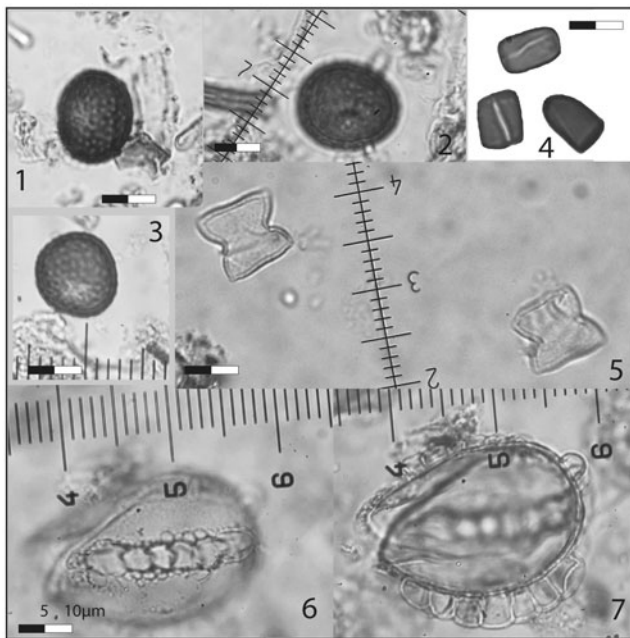


Fig. 3 Non-pollen palynomorphs from Igaliku, southwest Greenland. 1–3 IGA1, an unknown globose microfossil, 16–22 µm in diameter; 4 HdV-113, *Sporormiella*, ascospore, 6–9 × 10–13 µm; 5 HdV-371, *Tetraëdron* sp. Algae, hyaline, quadratic and cushion shaped microfossil, 17–19 × 19–21 µm; 6–7 *Filinia* resting eggs, 35–40 × 50–55 µm. HdV Hugo-de-Vries Laboratory, University of Amsterdam; IGA Igaliku

Plant macrofossils were present in small quantities, so eight samples of unidentified and mixed plant remains and six samples of well preserved terrestrial plant remains, such as *Betula* leaf, bark or twig, were dated. The dates obtained on terrestrial plant remains are generally later than the dates on samples with mixed remains of seeds and bryophytes (Table 1; Fig. 4). There is no carbonate around the lake, so there is no hard-water effect. This offset of about 400 years (Fig. 4) can be explained by the reworking of ^{14}C -depleted organic matter from the watershed and also by a particular reservoir effect which affects arctic lakes due to the recycling of old carbon (Abbott and Stafford 1996). Old dates were also reported by several authors after paired analyses of terrestrial macrofossils and bulk sediments or humic acid fractions at the same depth (Sandgren and Fredskild 1991; Kaplan et al. 2002; Edwards et al. 2008). So our samples of mixed plant remains probably contained aquatic plant fragments and/or old organic material remobilized by soil erosion and thus these dates were rejected (Fig. 4). Radiocarbon dates were calibrated to calendar years using the atmospheric calibration dataset IntCal04 (Reimer et al. 2004) by means of the OxCal 4.0 program (Bronk Ramsey 1995, 2001). Then, age–depth modelling, including the 1963 ^{137}Cs peak at 5.25 cm depth, was performed using a weighted regression procedure in the framework of generalized additive models (Heegaard et al. 2005). According to the ^{14}C calibration model, this depth–age curve is provided with a mean uncertainty close to ± 70 calibrated years.

The depth–age model shows a continuous and roughly linear sedimentation rate of 0.05 cm year⁻¹, with a slight increase to 0.065 cm year⁻¹ between 28 and 35 cm. Taken that the sediment surface reaches the present, the sediment accumulation above 10 cm, over the last 100 years, progressively increases to a maximum of 0.15 cm year⁻¹, which is probably an overestimate here because of the reduced compaction towards the sediment surface.

Results

Pollen and non-pollen palynomorph diagram

A simplified percentage diagram with selected curves of pollen and non-pollen palynomorph taxa (NPP) is presented in Fig. 5.

In Zone 1, regular pollen frequencies of *Betula pubescens* 20% (tree birch) and *Salix* 12%, *Betula glandulosa* 20%, *Juniperus* 5–8%, *Vaccinium* type, and *Empetrum-Ledum* type (willow/birch/juniper/heath scrub) are recorded and suggest the growth of these taxa in the catchment area. *Empetrum-Ledum* type and *Vaccinium* type (Ericaceous dwarf shrubs) are certainly under-represented in the

Table 1 AMS radiocarbon dates and ^{137}Cs results from Igaliku

Dating method	Depth (cm)	Lab. Code	Material	Radiocarbon age (B.P. $\pm 1\sigma$)	Calibrated age (1σ -range)	Calibrated age (2σ -range)
^{14}C	3,5-4,5	Poz-24707	Mixed plant remains	107,11 \pm 0,36 pMC		A.D. 1956-2007
^{137}Cs	5,5		Bulk sediment			1963
^{14}C	17-17,5	Poz-31628	Indet. Bryophyte	680 \pm 100	A.D. 1258-1399	A.D. 1155-1441
^{14}C	18-19	Poz-25024	Mixed plant remains	835 \pm 30	A.D. 1175-1251	A.D. 1156-1267
^{14}C	27,5-28,5	Poz-31632	<i>Betula</i> leaf	620 \pm 80	A.D. 1293-1398	A.D. 1260-1440
^{14}C	28,5-29,5	Poz-26851	Mixed plant remains	1070 \pm 30	A.D. 902-1015	A.D. 895-1021
^{14}C	31-31,7	Poz-31629	<i>Betula</i> bark	655 \pm 35	A.D. 1276-1328	A.D. 1276-1395
^{14}C	34,5	Poz-26852	<i>Salix glauca</i> leaf	775 \pm 30	A.D. 1225-1271	A.D. 1215-1281
^{14}C	40,5-41,5	Poz-26883	Mixed plant remains	2280 \pm 35	397-235 B.C.	402-208 B.C.
^{14}C	41,3-42,1	Poz-31630	<i>Betula</i> twig	945 \pm 35	A.D. 1030-1152	A.D. 1020-1165
^{14}C	44-45	Poz-24708	Mixed plant remains	1420 \pm 35	A.D. 608-652	A.D. 571-663
^{14}C	47,5-49,5	Beta-246872	Mixed plant remains	1580 \pm 50	A.D. 429-535	A.D. 384-597
^{14}C	55,5-56,5	Poz-24709	Mixed plant remains	2060 \pm 35	157-3 B.C.	173 B.C.-A.D. 19
^{14}C	64-65	Poz-30535	Indet. Bryophyte	1570 \pm 35	A.D. 434-537	A.D. 415-565
^{14}C	74,6-75,8	Poz-31633	<i>Betula</i> leaf	1580 \pm 60	A.D. 418-544	A.D. 343-605

Dates used in the age-depth model are in bold type. pMC means percentages of modern carbon

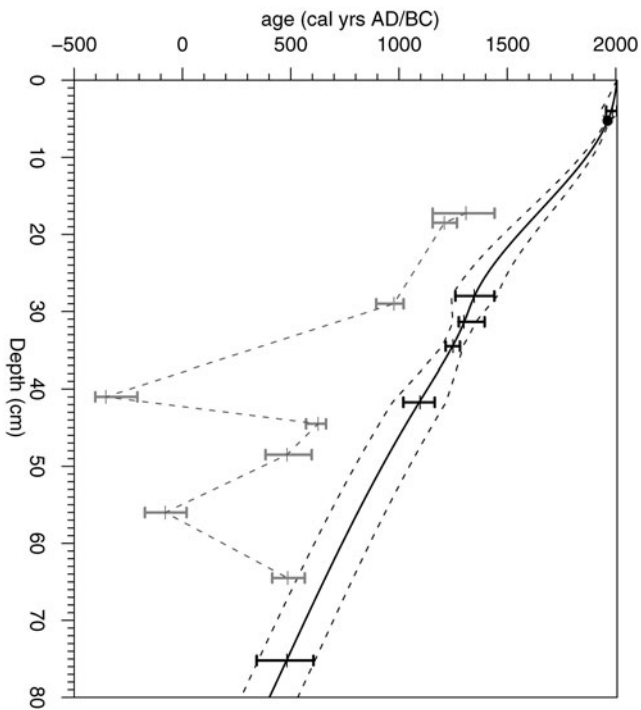
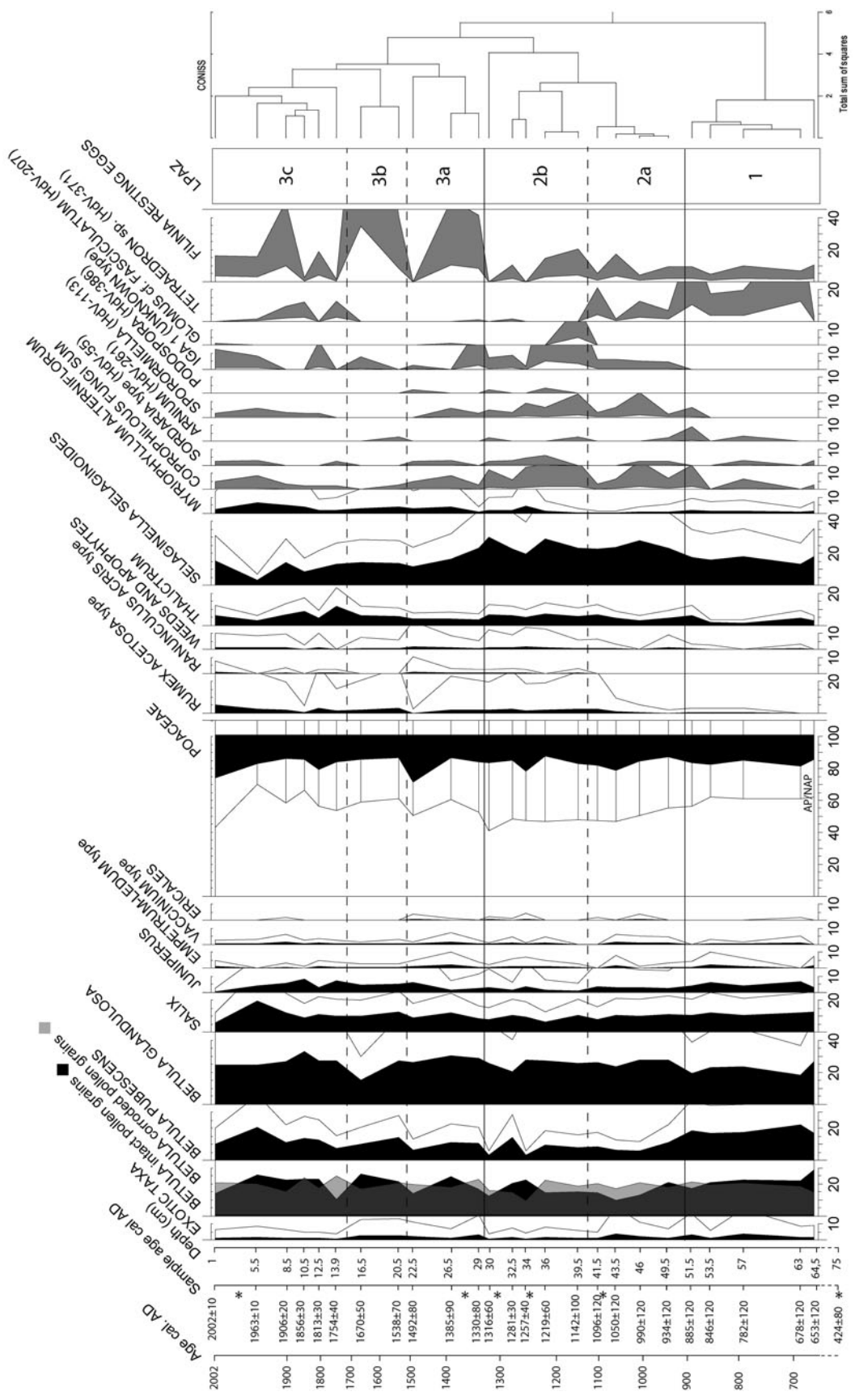


Fig. 4 Age-depth diagram for the lake sediments of Igaliku based on AMS radiocarbon dates from terrestrial plant macrofossils and a ^{137}Cs measurement (dot)

fossil pollen assemblage in comparison to birch and willow, which are overrepresented (Schofield et al. 2007b). This arctic cover allowed the expansion of *Selaginella selaginoides* (15–20%). *Rumex acetosa* type appears in this first zone, with very low percentages. Occurrences are

scarce among coprophilous fungi (*Sordaria* and *Arnium*). *Filinia* resting eggs have low values (2–3%). *Tetraedron* (5–12%), a small green alga, is characteristic of eu-mesotrophic conditions (Jankovská and Komárek 2000; Fig. 3), however, it can be observed in oligo-mesotrophic cold water and on lake littorals (Rybníčková and Rybníček 2006). *Myriophyllum alterniflorum* (2%—water milfoil) is an aquatic plant, tolerant of oligotrophic acid water such as boggy pool and is also characteristic of oligo-mesotrophic conditions.

The decrease in *Betula pubescens* (from 20 to 10%) and the rising values of *Selaginella selaginoides* (25%) and *Thalictrum* (4%) in LPAZ 2a suggest a more open area. Pollen evidence of moderate grazing pressure is recorded here, with a slight decrease in *Juniperus* (from 5 to 2%) and an increase in weeds/apophytes, and in corroded *Betula* pollen grains and in coprophilous fungi. The decrease in *Juniperus* has often been interpreted as an effect of grazing (Fredskild 1973). This shrub usually grows in places with only a slight snow-cover and is especially exposed to the attack of hungry herbivores. Increase in corroded *Betula* pollen grains could also be related to grazing pressure, as soil erosion under a cover of shallow-rooted permanent pasture may have caused an increase in the proportion of corroded pollen derived from eroded catchment soils (Lawson et al. 2007). The fungal spores of coprophilous fungi (*Sordaria*, *Sporormiella* and *Arnium*) indicate the presence of herbivore dung around the lake (van Geel and Aptroot 2006; Davis and Shafer 2006; Fig. 3). An unknown NPP appears (IGA 1; Fig. 3). The origin of this



◀ **Fig. 5** Simplified pollen and non-pollen palynomorph (NPP) diagram based on a relative percentage calculation. Exaggeration curves $\times 2$ for *Salix*, *Juniperus*, *Selaginella selaginoides*, *Thalictrum* and *Filinia* resting eggs, $\times 5$ for exotic taxa, *Vaccinium* type, *Empetrum-Ledum* type, Ericales, *Myriophyllum alterniflorum*, *Glomus* (HdV-201) and *Tetraëdron* sp., $\times 10$ for all other taxa. Exotic taxa: *Abies*, *Picea*, *Pinus*, *Carpinus*, *Corylus*, *Fagus*, *Fraxinus*, *Quercus*, *Ulmus*, *Ambrosia* and *Artemisia*. On the left, the age with the total standard deviation is given for each sample; asterisk denotes position of radiocarbon dates used for the age interpolation

microfossil remains difficult to determinate, and it could be a coprophilous ascospore or a spore of another origin, such as a bryophyte. Liverworts related to grazing and dung input are recorded in Greenland, *Riccia sorocarpa* Bisch. or *Marchantia alpestris* (Nees) Burgeff, for example. *Riccia* species grow abundantly in the emergent surfaces of regional mountain waters within areas of intense grazing (Carrión 2002a; Carrión et al. 2003). The use of bryophyte spores in pollen analyses has been demonstrated, however, the spore morphology of IGA 1 is very different, and as this type was also found in recent dung (see below) there is a good chance that the IGA 1 originates from dung. *Myriophyllum alterniflorum* and *Tetraedron* decrease, suggesting changes in water quality or lake level fluctuations (Jančová and Komárek 2000). At the end of LPAZ 2a, Poaceae and *Rumex acetosa* frequencies increase together with a perceptible decline of coprophilous fungi.

Vegetation change takes place in Zone 2b, with a slight decrease of willow and *Juniperus*, and increasing frequencies of *Rumex acetosa* type (Fig. 5). Poaceae representation is slightly reduced and *Ranunculus acris* type, another Norse apophyte very common today around farms and in pastures (Fredskild 1973, 1978) occurs for the first time. *Juniperus* reaches its lowest values (1%). *Selaginella selaginoides* is an acidophilic taxon and its rising frequencies (25–30%) suggest that the soils around the lake became increasingly leached over time, perhaps as a consequence of scrub clearance and grazing (Lawson et al. 2007). In combination with pollen data, the fungal record of coprophilous fungi, with the first occurrence of *Podospora*, suggests a high density of domesticated herbivores in the area under study. The unknown spore, IGA 1, increases suddenly; this unidentified microfossil obviously has the same trend as coprophilous fungi. *Tetraedron* nearly disappears. At the same time, the frequencies of *Filinia* resting eggs slightly increase (3–4%). The occurrence of *Glomus* cf. *fasciculatum* is correlated with the increased frequencies of corroded pollen grains of *Betula* sp. (Lawson et al. 2007). *Glomus* is found on the roots of a variety of host plants including *Betula* (van Geel 2001). Chlamydospores of *Glomus* observed in lake deposits, as well as corroded pollen grains, are indicative of soil erosion in the catchment of the lake. Coprophilous fungi decrease at the end of Zone 2b, suggesting a declining grazing pressure.

Zone 3a witnesses the steady decrease of coprophilous fungi. The slight regeneration of juniper and willow scrub constitutes a response to reduced grazing intensity. Coprophilous fungi nearly disappear in Zone 3b, contrary to *Rumex acetosa* type. Percentages of *Filinia* resting eggs and *Tetraëdron* are very irregular in Zone 3 and these fluctuations are difficult to interpret. Sometimes it seems to be related to human impact (van Geel 2001), but the highest values of *Filinia* occurred during a phase of decreasing human impact. In an attempt to explain the changes in the *Filinia* and *Tetraedron* records, we can suggest climatic oscillations of water temperature, duration of ice cover, trophic state, and perhaps some ecological causes such as the abilities of individual plants to spread and reproduce, or competition between taxa. The development of recent agriculture (LPAZ 3c) is linked to a new increase in *Rumex acetosa* type, weeds, coprophilous fungi and IGA 1.

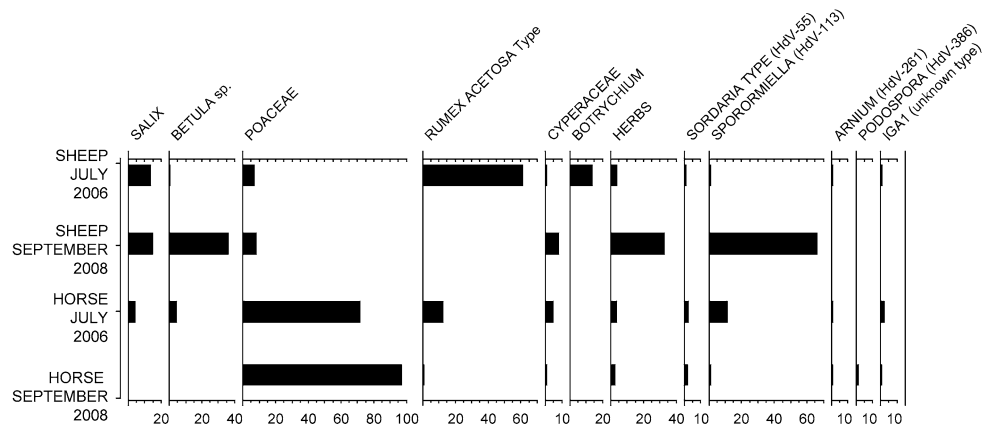
Pollen and NPP analyses from dung

Pollen extracted from dung samples represents what was consumed by herbivores as well as airborne pollen. Moe (1983) studied pollen from sheep faeces in Norway and concluded that it provides virtually no information about the quantitative composition of the vegetation of the sheep's environment, but it does provide valuable information about their diet. According to Carrión (2002b), dung pollen spectra represent ingested plant material from a local area. However, each leaf surface eaten by an herbivore may contain regional pollen rain. Coprophilous fungi recorded in samples grow in dung, but they could also have been ingested, if wind-dispersed ascospores were present on the grazed plants (Aptroot and van Geel 2006).

Sheep

The modern economy in southern Greenland is dependent upon sheep farming. Sheep graze almost everywhere, except in areas reserved for hay-making. Pollen analysis shows differences between July and September (Fig. 6). In the July sample, *Rumex acetosa* type is dominant (60%). However, the grazing of *Rumex* remains doubtful because the plant contains oxalates which are toxic for livestock. The analyses of pollen rain in Qassiarsuk (Schofield et al. 2007b) have shown very high frequencies of *Rumex acetosa* type (40%) in some of the field assemblages. The high frequencies encountered in our study are more the result of an overrepresentation of *Rumex* than from grazing it, for its pollen is present everywhere in the air, the vegetation and the water. Pollen of *Betula*, *Salix* and Poaceae are also frequently overrepresented in Schofield's study (2007b). Only *Betula* reaches high values in our September sample

Fig. 6 Pollen and non-pollen palynomorph analyses of modern sheep and horse dung samples from the Igaliku area, Greenland, on a relative percentage calculation



and could be overrepresented. The season for *Betula* pollination is finished in September, but sheep are known to appreciate shrub leaves. This is a factor in limiting tree and shrub growth (Fredskild 1973; Schofield et al. 2007a). The *Betula* pollen frequency from the September sample is probably related to leaf grazing and the ingestion of pollen grains remaining on shrubs. The record of coprophilous fungi shows occurrences of *Sordaria*, *Sporormiella* and *Arnium*, the very same taxa recorded in the fossil sediment samples. *Sporormiella* is the dominant taxon in the September dung sample. IGA 1 type, the unknown taxon, is also present but it seems a little more abundant in horse dung.

Horses

They often live close to farms, and they are of invaluable assistance at the end of summer, when Greenlandic farmers use them to bring in the sheep which are scattered across large areas. High frequencies of Poaceae (70 and 95%; Fig. 6) are probably related to the fodder given to the horses by farmers because pollen dispersal by Poaceae is quite weak by September. There is no dominant taxon among the coprophilous fungi, and all the taxa found in sheep dung also occur in horse dung with low frequencies.

Discussion

LPAZ 1 covers the period prior to the arrival of farmers (ca. A.D. 650–900; Fig. 5). Low arboreal and dwarf-shrub pollen frequencies indicate a regionally open landscape without any evidence of human activities until A.D. 900. Discreet occurrences of *Rumex acetosa* type are recorded and could result from long-distance pollen transport from Europe or America. This taxon has also been reported in a pre-settlement phase at Coramum Sø (Fredskild 1973). The pollen type includes *Rumex acetosa*, *R. acetosella* and

Oxyria digyna pollen grains (Beug 2004). The latter is native to Greenland but *R. acetosa* and *R. acetosella* are, according to Fredskild (1973), Norse apophytes. However, there are two ecologically different strains of *R. acetosella* in Greenland, the first one an indigenous strain, distributed in west Greenland south of ca. 71° and towards northeast Greenland between 70° and 75°, while the other, hemerophilous, strain is only found in Norse settlements (Fredskild 1973). Occurrences of local *Oxyria digyna*, or *R. acetosella* indigenous strain, an anemophilous and prolific pollen producer (Fredskild 1973), do not seem exceptional in these conditions.

LPAZ 2a is dated between ca. A.D. 900 and 1100, which is within the Medieval Warm Period (MWP) ca. A.D. 885–1235, according to Lassen et al. (2004). The westward expansion of Norse settlers into the wider North Atlantic region took place precisely during this period, and the first farmers are supposed to have arrived in Greenland by the end of the 10th century A.D. (Amorosi et al. 1997). The environmental changes in the pollen diagram, an increase in coprophilous fungi at ca. A.D. 900 and a decline of *Betula pubescens* after A.D. 950, could be related to the first stage of the colonization (Fig. 5). However *R. acetosa* type remains scarce. Previous studies have often dated the increasing frequencies of *R. acetosa* type in the Eastern Settlement from the time of the very beginning of colonisation (Fredskild 1973, 1978; Schofield et al. 2007a; Edwards et al. 2008; Buckland et al. 2009). Our age–depth model suggests that the discrepancy between the fall of *Betula pubescens*, maybe if birchwood was used domestically for cooking or heating purposes, and the expansion of *R. acetosa* type, may have been in the order of 100 years. What could be the reasons for such an event: a pre-Norse human impact without introduction of *R. acetosa* type (the age–depth model allows this hypothesis)? Was it a delay in the acclimatization of *R. acetosa* type? Was it grazing by wild herbivores with an increase in coprophilous fungi, or was climatic change responsible?

The warming conditions of this period (Crowley 2000; Lassen et al. 2004) cannot explain all the changes in the vegetation. For instance, the decrease in *Betula pubescens*, which only grows in southern Greenland, is in contradiction with a warming climate. Climate change does not support the decline in *Myriophyllum spicatum* either. Isarin and Bohncke (1999) mention that the presence of this aquatic plant indicates a minimum mean July temperature of 9°C. Igaliku is close to this ecological limit with a mean July temperature of 10.3°C from 1961 to 1990 at Narsarsuaq (Cappelen et al. 2001). The decrease in *Myriophyllum alterniflorum* could be caused by a climate cooling but Zone 2a occurs during the MWP (Crowley 2000; Lassen et al. 2004; Moberg et al. 2005). *M. alterniflorum* percentages do not seem to be affected during the Little Ice Age (LIA) period (~A.D. 1350–1850) in Zone 3. Thus we assume that the decrease of *M. alterniflorum* is more likely due to changes in water quality than to a climatic change.

The clearance of birch trees creates open habitats suitable for grazing by herbivores, and the rise in ascospores of coprophilous fungi is generally attributed to the presence of dung from livestock in the catchment area. We have to underline that coprophilous fungi grow in the dung of all herbivores, and wild herbivores overgrazing the area could also have transformed the environment. However, we are in a period of warmer climate and this would not favour a large population of reindeer. Reindeer calves are born in spring when nutritious plants are growing. The earlier appearance of green growth accompanies warmer spring temperatures, but the timing of caribou/reindeer calving has not shifted to correspond with peak forage availability (Post and Forchhammer 2008). Mother and calf are not able to exploit high-quality forage during a period of high energetic requirements, taxing female body condition and consequently lowering calf production (Post and Forchhammer 2008; Vors and Boyce 2009). So, natural causes such as climate change and wild herbivore grazing cannot really explain the environmental change in LPAZ 2a. In spite of the scarcity of *Rumex acetosa* type, the recorded change in the pollen diagram could be linked with pastoral activities.

Human activities could be responsible, but the Norse apophyte *R. acetosa* type keeps low values. Could we consider a pre-Norse settlement, without the introduction of *R. acetosa* type? The standard deviation of the depth–age model (± 120 years) as shown does not provide evidence of human impact earlier than the date given by historical sources. Nevertheless, previous studies have recorded early agricultural impact in the Eastern Settlement. At Galium Kaer, human impacts appear at A.D. 660–1030 (K-1647; 2σ) (Fredskild 1973), and at Søndre Igaliku anthropogenic indicators appear from at A.D. 596–877 (B-5311; 2σ) (Sandgren and Fredskild 1991). However, these

dates were rejected by the above authors because they did not concur with the chronology of the historical sagas. We have also rejected older radiocarbon dates because of reservoir effects. Early settlements, earlier than the historical data, have been observed in North Atlantic Islands. The Faeroe Isles were settled, according to historical texts, by ca. A.D. 860 (Amorosi et al. 1997). Hannon and Bradshaw (2000) have established a different chronology. They show the first occurrence of cultivated crops as early as the 6th century A.D. and the introduction of domestic animals by ca. A.D. 700.

Concerning the expansion of *R. acetosa* type, Edwards et al. (2008) suggested a delay of about 30 years between the first clear evidence for human impact and a sustained rise in the *R. acetosa* type pollen curve. In the Igaliku pollen diagram, the age–depth model suggests a delay of about 100 years. According to historical sources, a Norse farmer recorded as accompanying Erik the Red from Iceland was the first settler of Igaliku/*Garðar* (Buckland et al. 2009). Erik the Red's daughter also lived in Igaliku, but the settlement grew from A.D. 1124 when the episcopal seat of *Garðar* was created. In the pollen diagram, the maximum percentages of *R. acetosa* type are precisely dated to ca. A.D. 1100. The vegetation change in phase 2a could also be the result of the first historical settlement, before the expansion of *Garðar* and the delay in the expansion of *R. acetosa* type was maybe longer than expected.

Recorded events in Zone LPAZ 2b (ca. A.D. 1140–1320; Fig. 5) correspond to the well-known Norse *landnám*: the increased pollen from likely Norse apophytes such as *R. acetosa* type and *Ranunculus acris* type and NPPs with a peak of *Glomus cf. fasciculatum* and an increase in *Sporormiella*, *Sordaria*, *Arnium* and IGA 1 do not leave any doubt about grazing pressure and human impact. Coprophilous fungi reach their maximum values and, among these fungal remains, *Podospora* occurs for the first time, and could be related to the first presence of cows, as this phenomenon is known from sites in Austria, the Azores and Tibet (Jean Nicolas Haas and Jacqueline van Leeuwen, personal communication). The increasing proportion of livestock (cows, pigs, sheep and goats) as well as the spread of midden material on hayfields in order to improve yields (Graf and Chmura 2006; Buckland et al. 2009) may have brought a large amount of ascospores into the lake sediments. The general trend of declining coprophilous fungi and corroded *Betula* pollen grain values is evident at the end of LPAZ 2b (ca. A.D. 1260–1320) and suggest a decreasing grazing pressure and/or manuring of hay fields. According to the archaeological data and isotopic studies by Arneborg et al. (1999, 2002), the average diet of the Norse people progressively changed from 20% marine food around A.D. 1200 to 80% marine food at the end of the settlement around A.D. 1450. This change with time is

probably due to an adaptation to the changing climate. This decrease in grazing pressure seems to be linked with an economic change most probably caused by the climatic transition from the Medieval Warm Period to the Little Ice Age.

In LPAZ 3a (ca. A.D. 1330–1500; Fig. 5) frequencies of *Thalictrum*, weeds and apophytes, *Selaginella selaginoides* and coprophilous fungi all decline. Reduced farming activity is the prelude to the end of the settlement in the beginning of the 15th century A.D. This date is consistent with historical data and pollen analyses (Schofield et al. 2007a; Buckland et al. 2009), and coincides approximately with the evidence for the onset of the Little Ice Age. Effects of the LIA on the vegetation are not evident in this pollen diagram (LPAZ 3a and b). *R. acetosa* type seems to hold its ground to some extent but it does not seem to be a very good anthropogenic indicator. It could occur before any settlement (LPAZ 1—long distance transport or indigenous strain), it maybe needed a delay to really adapt to the harsh Greenlandic climate (LPAZ 2a), and it does not disappear after the abandonment of the site (LPAZ 3). Coprophilous fungi seem here to be the most reliable indicators for farming activities and grazing pressure.

Conclusions

- According to our pollen and non palynomorph data, the first colonization may have been around A.D. 885 ± 120 . The standard deviation of the depth–age model does not allow us to suggest a human impact earlier than the date given by historical sources. The first settler of Igaliku/*Garðar* accompanied Erik the Red in A.D. 985. From ca. A.D. 1100 the development of farming activities did exert a perceptible impact on the environment.
- The palynological signal shows an increase in coprophilous fungi and the clearance of *Betula pubescens*, however there is a clear discrepancy of about 100 years between this first human impact and the expansion of the likely Norse apophyte *Rumex acetosa* type. The delay between the introduction and the expansion of *R. acetosa* type was maybe longer than expected.
- The first colonization phase is followed by a period of decreasing human impact in the beginning of the 14th century A.D. The regrowth of birch and the disappearance of anthropogenic indicators except *R. acetosa* type between the 15th and 18th century demonstrate the abandonment of the settlement, until the development of modern agriculture in the 20th century.
- The same ascospores from coprophilous fungi and those related to animal husbandry are recorded in lake sediments and modern dung samples. The unknown

spore IGA 1 is of particular interest: its curve has the same trend as those of other coprophilous taxa and it also occurs in the dung samples. Non-pollen palynomorphs are of invaluable help here in demonstrating the introduction of domesticated herbivores, inferred grazing pressure and/or spread of manure in order to fertilize. Coprophilous fungi provide an accurate vision of the historical colonization of Greenland, complementing historical and archaeological knowledge.

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