The biogeographical status of *Alnus crispa* (Ait.) Pursch in sub-Arctic southern Greenland: do pollen records indicate local populations during the past 1500 years?

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Abstract

Phytogeographical studies of southwestern Greenland suggest that *Alnus crispa* is not native to the far south of the island. Palynological investigations dating to the 1970s concluded that this was the case throughout the Holocene, with the regular occurrences of *Alnus* seen in pollen diagrams from this region explained as the result of long distance transport of alder pollen from Canada. Recently, macrofossil evidence from an archaeological site in southern Greenland has emerged that indicates that alder was amongst the fuel resources available to the Norse settlers around AD 1000-1400. In light of this discovery, we present data from thirteen pollen diagrams produced since 2008 to re-examine the past status of *Alnus* within southernmost Greenland over the last 1500 years. Only at one site with a very large pollen source area do *Alnus* pollen frequencies regularly exceed a threshold which may be interpreted as indicating a regional presence for the plant. This pattern is argued to be consistent with the presence of a small but variable regional population of the plant, perhaps restricted in its distribution to the inland district of Vatnahverfi.

Keywords: *Alnus crispa*, pollen, Greenland, Norse Eastern Settlement, pollen threshold values, biogeography

Introduction

Alnus crispa (Ait.) Pursch (green alder or mountain alder) is the only species of alder native to Greenland (Böcher et al. 1968; Fig. 1A) and is synonymous with *Alnus viridis* (Chaix) DC. ssp. *crispa* (Aiton) Turill, which is widespread throughout Canada and several states in the northeastern USA (USDA NRCS 2014). The plant has a modern distribution in Greenland that extends across the area between ~61-66°N and ~47-52°W (Laegaard 1971; Feilberg 1984; Fredskild 1996; Fig. 1B) where it forms thickets or scrub communities, most typically in association with *Salix glauca*. *Alnus* is commonly recorded in Holocene pollen diagrams outside this range, notably south of 61°N and east of 47°W, in the area that approximately corresponds with the former Norse Eastern Settlement (Krogh 1967) and is referred to by Böcher et al. (1968) as the floristic province of southernmost Greenland (Fig. 1C). Fredskild (1973) was the first to draw attention to this phenomenon in a series of pollen diagrams that allowed an assessment of the development of the Greenlandic flora since the start of the Holocene. The widespread absence of *Alnus crispa* from southern Greenland today led Fredskild (ibid.) to attribute all *Alnus* pollen in his diagrams from lakes around Kap Farvel and Qassiarsuk to extra-regional sources (*sensu* Janssen 1973), arriving on the prevailing westerly and southwesterly winds from Labrador and adjacent parts of Canada, something which is evident in more recent data (e.g. Rousseau et al. 2005, 2008; Jessen et al. 2011).

Over the past ten years, palaeoecological investigations into the fate of Norse settlers in the Eastern Settlement have furnished thirteen new pollen profiles from this region (Edwards et al. 2008, 2011; Schofield et al. 2008; Buckland et al. 2009; Golding et al. 2011; Schofield and Edwards 2011; Massa et al. 2012; Ledger 2013; Ledger et al. 2013, 2014a, 2014b, 2015) more than doubling the available information (Figs 1C, D, and E). Typically, the temporal extent of these sequences is short in comparison to earlier work (e.g. Fredskild

1973) and they are largely focused upon events over the last two millenia, but the majority of recent studies benefit from higher resolution analysis and improved radiocarbon dating. In addition, a recent archaeobotantical study from the Vatnahverfi region of the Eastern Settlement has identified nutlets and roundwood charcoal of *Alnus* sp. in deposits of Norse age (Bishop et al. 2013), which provides strong evidence that the plant was growing locally in at least some places. In light of this macrofossil find, this paper synthesises the new palynological data for the region to reconsider the biogeographical status of *A. crispa* in southern Greenland over the last ~1500 years, and to ask whether small populations of the plant may once have been more common in this area than has previously been thought.

Distribution and environmental preferences of A.crispa

A.crispa is a tall shrub or low tree found in the subcontinental middle fjord or inland areas of western Greenland. The plant appears to show little firm preference in terms of substrate, forming scrub over moist ground adjacent to streams and rivers (Böcher et al. 1968), but also noted as growing on more well-drained soils (Kelly and Funder 1974). The northern tree line for the species – around Kangerlussuaq (Søndre Strømfjord) ~66ºN – appears to be fixed by decreasing summer temperatures in coastal areas and by highly xeric conditions in the interior, whilst the southern limit (~61ºN) appears to be determined by increasing oceanicity, or competition with *S. glauca*, or both (ibid.).

Fredskild (1973, p.198-199) reports two isolated occurrences of *A.crispa* in southern Greenland that are outside the general range for the plant as described earlier; one record is noted at a position ~50 km northwest of Qaqortoq (60º56’N, 46º48’W), and a second appears in Vatnahverfi, ~10 km southeast of Igaliku Kujalleq (~60°52’N, 45°4’W). The reasons why *A. crispa* is not widely present today in southernmost Greenland still remain somewhat unclear given that the climatic conditions in that region are similar to those experienced along the Labrador coast where *A. crispa* is common (Fredskild and Ødum 1990).

Physical geography of the study area

The landscape of southern Greenland is dominated by steeply rising mountains which sharply shelve into a deep network of fjords. Although mountainous, there are also isolated low-lying plains and inland valleys with numerous lakes. Climatically the region is characterised by a strong temperature and precipitation gradient between the outer coast and the inland ice margin. The coasts and the outer reaches of the fjords experience an oceanic/maritime climate, whereas more continental conditions are experienced towards the heads of the fjords (Feilberg 1984). This variation heavily influences the vegetation of the region (Fig. 1C). Coastal areas (oceanic low-Arctic) are dominated by dwarf-shrub heaths in which *Empetrum nigrum* and *Vaccinium uliginosum* are important (Böcher et al. 1968; Feilberg 1984). Moving inland, *Betula glandulosa* and *S. glauca* heath and scrub vegetation are better developed and become dominant. Elements of this community can reach up to 3 m in height, and in sheltered locations, open *Betula pubescens* woodland may occur. It is in similarly continental settings that *A. crispa* is found elsewhere in southern Greenland (Feilberg 1984; Fredskild 1996).

Early palaeoecological data

Fredskild's (1973) pollen data from southern Greenland is geographically concentrated in the subcontinental sub-Arctic (three sites) and oceanic low-Arctic vegetation zones (three sites), with one site located in the suboceanic sub-Arctic zone (Fig. 1C). The datasets derive from a mixture of small to medium-sized lakes and small mires (Table 1). Maximum *Alnus* percentages for the region approach 20% TLPS (total land pollen and spores) during the mid-Holocene (c. 7,800-5,800 cal. BP) in some lakes (e.g. Isoëtes Sø) around Kap Farvel (in the oceanic low-Arctic vegetation zone). Thereafter these values decline to c. 2-5% in the late postglacial. Further north, in the lakes and mires of the subcontinental sub-Arctic zone, *Alnus* pollen is never more than a rare occurrence throughout the Holocene. This pattern can be compared with *Alnus* pollen frequencies recorded in modern samples collected from various different depositional contexts (recent gyttja, moss polsters, Tauber traps and surface litter/soil). These are typically 0.5% and 1.5% in southern interior and coastal locations respectively (Fredskild 1973; Schofield et al. 2007), whereas mean values within the interior of western Greenland – the area that currently contains alder (Fig. 1B) – are much higher at approximately 12.5% (Fredskild 1983).

Alnus is widely recognised as a high pollen producer and it is considered to be over-represented in pollen diagrams (Davis 1963; Anderson 1970; Broström et al. 2008). On the basis of the relatively low pollen frequencies noted above, Fredskild (1973) dismisses the possibility of *A. crispa* ever having grown in southern Greenland at any point during the Holocene. Instead he suggests that the *Alnus* pollen in palaeoecological records from southern Greenland is exotic and the result of long distance transport, mainly from interior Labrador, where mid-Holocene pollen frequencies were high, with peak values of ~75% TLP (total land pollen) across seven sites from c. 6,200-5,800 cal. BP (Morrison 1970; Fredskild 1983). These frequencies were to decline considerably during the late Holocene (i.e. after c. 4,000 cal. BP). More recent pollen-analytical studies from regions adjacent to Labrador also report very high frequencies of *A. crispa* pollen through the Holocene; for example, Gajewski et al. (1993) have produced four pollen diagrams for northwest Québec in which peak values of >40% for *A. crispa* are recorded c. 6,000-5,000 cal. BP, whilst Richard (1994) shows *A.*

crispa pollen frequencies have fluctuated between ~30-85% through the full span of the Postglacial at sites around the eastern St Lawrence River (southern Québec).

There is also debate surrounding the arrival time of *A. crispa* in western Greenland (61-66°N). In the early Holocene (from c. 8,000 cal. BP) *Alnus* pollen increases, as is the case in the Kap Farvel region, to c. 10-20% TLPS in a series of lakes around 62-64°N (Fredskild 1973; 1983; Kelly and Funder 1974) and from 5,000 cal. BP *Alnus* pollen percentages of c. 5% TLP have also been recorded around 67ºN (Eisner et al. 1995). However, a number of these sites are located in the outer fjords which are (and perhaps always were) climatically unsuitable for the growth of *Alnus*. Fredskild (1983) therefore invoked long distance transport as the source of the first rise in alder pollen in west Greenland diagrams, suggesting that a later sustained rise in *Alnus* pollen after c. 4,000 cal. BP at interior sites reflects the immigration of *A. crispa*. This view is contested by Kelly and Funder (1974) who argued that alder in Canada was never sufficiently widespread or persistent to have dominated the exotic pollen transported to Greenland. Rather, they prefered to interpret the often high percentages (>10%) of *Alnus* pollen recorded in their pollen diagrams around the Paamiut region (~62ºN) as representative of the local growth of alder copses from perhaps as early as c. 8,400 cal. BP. It should be noted that these ideas were formulated at a time when pollen-analytical studies in eastern Canada were still relatively few in number (see Ritchie [1987] for an early review of this material), and a reappraisal of the situation may now be necessary.

Materials and Methods

This paper presents a compilation of *Alnus* pollen data from thirteen sites that have been published since 2008 (Fig.1, Table 2). In each of these studies the identification of alder pollen to species level was not attempted as there is debate surrounding how secure such determinations are (cf. Mayle et al. 1993; May and Lacourse 2012). The records presented here from Greenland are taken to represent (predominantly) the pollen of *A. crispa*, although very minor inputs of long-distance transported pollen of *Alnus incana* (syn. *A. rugosa*; Scoggan 1978) – which is also widespread across northern North America but not found in Greenland (USDA NRCS 2014) – should not be entirely discounted. Traces of pollen of *A. incana* have been reported as present in modern pollen assemblages from north of the latitudinal treeline both in northwest Quebec and on several of the eastern Canadian Arctic islands (Gajewski 1991; 2002), although in each case the frequencies for *A. incana* were heavily outweighed by pollen input from *A. crispa*.

The *Alnus* data are expressed as percentages of total land pollen (TLP), and these are plotted against the chronologies (calendar years AD) from the cited publications. In all instances, the ages of samples reflect the median or best fit ages from the relevant age-depth models. All data (Fig. 2) were entered into TILIA and plotted using TGView (Grimm 1993, 2015) with the exception of the percentage values from Lake Igaliku (Massa et al. 2012) which were abstracted from the original publication.

Results

The new data from southern Greenland are predominantly derived from relatively small sites that are comparable to the mires examined by Fredskild (1973). Precise basin dimensions are available for six of the thirteen sites listed. Of these, only one profile – Saqqaata Tasia in Vatnahverfi (Ledger et al. 2014b) – is similar in size and depositional context to the lakes of the Kap Farvel region, while Lake Igaliku (Massa et al. 2012) is by far the largest site examined. Geographically, the profiles are biased towards the subcontinental (9 sites) and suboceanic zones (3 sites) with only a single profile, Sandhavn, located in the oceanic zone

(Fig. 1C). Of the thirteen profiles, only four record *Alnus* values of ≥1%; these are the larger basins, and those located in the suboceanic and oceanic vegetation zones (Fig. 2). Lake Igaliku is the only site where *Alnus* is consistently present. Throughout the last 1500 years at Lake Igaliku, *Alnus* is recorded in every sample at c. 1-3%. At Saqqaata Tasia there are three peaks above 1%, occurring around AD 1000 and 1200, and then later in the 17th century; the latest of these dates is coeval with values of up to 2% at Nimerialik in southern Vatnahverfi (Fig. 2). The only other profile surpassing >1% is that from Sandhavn where *Alnus* reaches 1.6% around the middle of the 20th century. At the remainder of the sites, *Alnus* is regularly recorded at trace values, with no obvious spatial or temporal patterning evident. The only site to show a sustained period of *Alnus* absence is Sissarluttoq, where there is only a single occurrence between AD 1300 and 1950.

Discussion

Was A. crispa widely present in southern Greenland during the last 1500 years?

The results of the analysis of the new palaeoecological data covering the past c. 1500 years highlight two patterns which are in agreement with the findings of Fredskild (1973). These are that the highest *Alnus* values are recorded in: (i) the larger basins; and (ii) at the more coastal and southerly sites. The first of these findings is probably explicable taphonomically in terms of the relationship between basin size and pollen source area. Larger basins recruit pollen from a much wider region than smaller ones (Jacobson and Bradshaw 1981; Davis 2000; Sugita 2007) and they are better reflectors of pollen that is transported over long distances. This would explain why *Alnus* pollen percentages at Lake Igaliku are consistently ≥1%, while neighbouring basins record only rare occurrences. The apparent north to south gradient of slightly increasing *Alnus* percentages is less easily explained. Nevertheless, it may relate to the increased exposure of the more southerly sites to the westerly track of air masses across the North Atlantic. These air masses, arriving from eastern North America, are responsible for the majority of the precipitation experienced in southern Greenland (Chen et al. 1997; Jessen et al. 2011) and would have ample opportunity to become enriched in *Alnus* pollen (e.g. Rousseau et al. 2006). As the more coastal and southerly regions experience enhanced precipitation relative to the heads of the fjords, it would also follow that there would be increased deposition of long distance pollen in these areas.

Although such an explanation is generally consistent with the interpretations of Fredskild (1973), it may not explain all *Alnus* occurrences in the pollen record. Fredskild (ibid.) recorded isolated stands of *A. crispa* in southern Greenland (described above) and the recent discovery of charred alder macrofossils, including roundwood (pith to bark) and an *Alnus* nutlet, in a Norse archaeological context at Timerliit (Norse ruin group Ø69) in Vatnahverfi (Bishop et al. 2013) suggests that the plant was growing locally. The macrofossil assemblage from this site also includes charcoal from a number of tree genera not native to Greenland (e.g. *Abies*, *Larix* and *Pinus*). This probably results from the burning of driftwood brought on to the site (cf. Malmros 1994), yet it seems highly unlikely that the discovery of a small and delicate macrofossil such as charred nutlet could be explained in the same way. Given this evidence it is not unreasonable to assume that at least some of the *Alnus* pollen noted in pollen diagrams is derived from local populations. Indeed, the consistency of *Alnus* pollen in the profiles dating from the last 1500 years compared with that of *Picea* (Figure 3), which is undoubtedly ‘exotic’, suggests that this may be the case. Long distance pollen transport is erratic and subject to changing climatic dynamics such as prevailing wind directions (Janssen 1973). This is perhaps illustrated in the data from Isoëtes Sø, Kløftsø, and Spongilla Sø (Table 1), which record variable *Alnus* values throughout the Holocene

(Fredksild 1973), as well as in studies of modern long-distance pollen transport over Greenland that indicate a high degree of temporal and spatial variability (Rousseau et al. 2008).

Deciding when a plant species is present in a geographical area on the basis of its pollen abundance in sediments is far from simple. Concepts such as the *empirical limit* – the point at which pollen from the species becomes consistently present – and the *rational limit* – the point at which the pollen curve begins to rise to steady values – have been respectively used to indicate the appearance and expansion of a taxon (e.g. Smith and Pilcher 1973; Bennett and Birks 1990). Other studies advocate using threshold values to differentiate between locally-produced and long-distance transported pollen (Lisitsyna et al. 2011). Although the latter might be viewed as the more rigorous approach, there is often little consistency between the threshold values set by different investigators. For example, *Alnus* pollen percentage thresholds fixed for different geographical areas of Europe vary from as little as 0.5% TLP in Poland (Szczepanek et al. 2004) to as much as 8% in Norway (Moe and Odland 1992). On the basis of the analysis of contemporary and potential vegetation maps, and modern pollen samples, Lisitsyna et al. (2011) propose using threshold values only as indicators of the regional presence of plants, and in the case of *Alnus*, recommend 2.5% TLP. *Alnus* pollen frequencies from Lake Igaliku (Massa et al. 2012) exceed this threshold in some, but not all, samples. This pattern might be consistent with the presence of small but variable regional populations of the plant, perhaps located at some distance from the sites with much smaller pollen source areas.

Unfortunately it is difficult to use the 2.5% TLP threshold proposed by Lisitsyna et al. (2011) to ascertain how extensive *Alnus* was across southern Greenland, or where such populations may have grown. Nevertheless, a cursory examination of the *Alnus* curves (Fig. 2) which pre-date the onset of Norse settlement in the late 10th century, hint at alder populations in the vicinity of some of the Norse farms (e.g. Tasiusaq, Sissarluttoq, Saqqaa, the Mountain Farm, Lake Vatnhaverfi, and Nimerialik). At each of these sites, there are declines in *Alnus* either upon settlement, or from the mid-12th to early 13th centuries. This pattern may indicate that small *A. crispa* populations were present at the time of Norse settlement and latterly cleared. It must be stressed that these changes are minor and for constrained time-spans in some instances, but they run contrary to what would be expected on the basis of *Alnus* frequencies recorded in pollen diagrams from the proposed exotic sources areas in Canada. After c. 1000 cal. yr BP there is either little change, or a gradual increase, in *Alnus* pollen percentages in sites in central Québec and coastal Labrador (Short and Nichols 1977; Gajewski et al. 1993). These data therefore suggest that there was potentially an increased availability of *Alnus* pollen for long distance transport to southern Greenland during this period. Indeed, a fjord sediment core from southern Greenland does record increased *Alnus* pollen percentages at this time (Jessen et al. 2011). Although these data are far from conclusive, they do hint at the possibility of scattered populations of alder in the Vatnahverfi region. Where the records are more sporadic, or do not pre-date settlement, it is difficult to make any observations regarding the status of *A. crispa*.

Conclusions

On the basis of this synthesis, it appears that Fredskild's (1973) conclusion that *Alnus* has never been indigenous to southern Greenland requires revision. Macrofossil evidence (Bishop et al. 2013) suggests that alder was present (or available) in at least one location within Vatnahverfi during the last 1500 years. Indeed, *Alnus* is most abundant and persistent in the pollen diagrams from this region when compared with other sites in southernmost Greenland for which palynological data are currently available. Collectively, the pollen and macrofossil evidence, plus the modern botanical record from Igaliku Kujalleq, seemingly points to some isolated stands of alder in Vatnahverfi. This seems plausible given the relatively continental climate that this region experiences, which closely matches the ecological requirements for *A. crispa*.

Although this paper has exclusively considered the last 1500 years in southern Greenland it also has implications for the interpretation of palaeovegetation records from earlier periods in the Holocene and regions further north in Greenland. In light of the analysis presented here, earlier records of *Alnus*, both in the north and south of Greenland, may in fact reflect isolated populations of greater antiquity than the (late Holocene) period of interest featured in this paper.

Acknowledgements

The Leverhulme Trust is thanked for financial support. We also thank the referees for their constructive comments that helped to improve the paper.

Conflict of Interest: the authors declare that they have no conflict of interest.

Research involving human participants and/or animals: this article does not contain any studies with human participants or animals performed by any of the authors.

Informed consent: “Informed consent was obtained from all individual participants included in the study.”

References

Andersen ST (1970) The relative pollen productivity and pollen representation of North European trees, and correction factors for tree pollen spectra. Danmarks Geologiska Undersøgelse II 96:1–99.

Bennett KD, Birks HJB (1990) The postglacial history of alder (*Alnus glutinosa* (L.) Gaertn.) in the British Isles. J Quaternary Sci 5:123–133.

Bishop RR, Church MJ, Dugmore AJ, Madsen CK, Møller NA (2013) A charcoal-rich horizon at Ø69, Greenland: evidence for vegetation burning during the Norse *landnám*? J Archaeol Sci 40:3890–3902.

Böcher TW, Holmen K, Jakobsen K (1968) The Flora of Greenland. P. Hasse & Son, Copenhagen, Denmark.

Broström A, Nielsen AB, Gaillard M-J, Hjelle K, Mazier F, Binney H, Bunting J, Fyfe R, Meltsov V, Poska A, Räsänen S, Soepboer W, von Stedingk H, Suutari H, Sugita S (2008) Pollen productivity estimates of key European plant taxa for quantitative reconstruction of past vegetation: a review. Veg Hist Archaeobot 17:461–478.

Buckland PC, Edwards KJ, Panagiotakopulu E, Schofield JE (2009) Palaeoecological and historical evidence for manuring and irrigation at *Garðar* (Igaliku), Norse Eastern Settlement, Greenland. Holocene 19:105–116.

Chen QS, Bromwich DH, Bai LS (1997) Precipitation over Greenland retrieved by a dynamic method and its relation to cyclonic activity, J Climate 10:839–870.

Davis MB (1963) On the theory of pollen analysis. Am J Sci 261:897–912.

Davis MB (2000) Palynology after Y2K-Understanding the Source Area of Pollen in Sediments. Annu Rev Earth Pl Sci 28:1–18.

Edwards KJ, Schofield JE, Kirby JR, Cook GT (2011) Problematic but promising ponds? Palaeoenvironmental evidence from the Norse Eastern Settlement of Greenland. J Quaternary Sci 26:854–865.

Edwards KJ, Schofield JE, Mauquoy D (2008) High resolution palaeoenvironmental and chronological investigations of Norse *landnám* at Tasiusaq, Eastern Settlement, Greenland. Quaternary Res 69:1–15.

Eisner WR, Törnqvist TE, Koster EA, Bennike O (1995) Palaeoecological studies of a Holocene lacustrine record from the Kangerlussuaq (Søndre Strømfjord) region of West Greenland. Quat Res 43:55–66.

Feilberg J (1984) A phytogeographical study of South Greenland. Vascular Plants. Meddelelser om Grønland, Bioscience 15:15–69.

Fredskild B (1973) Studies in the vegetational history of Greenland. Meddelelser om Grønland 198:1–245.

Fredskild B (1983) The Holocene vegetational development of the Godthåbsfjord area, West Greenland. Meddelelser om Grønland, Geoscience 10:1–28.

Fredskild B (1996) A phytogeographical study of the vascular plants of West Greenland (62° 20'-74°00'N). Meddelelser om Grønland, Bioscience 45:1–157.

Fredskild B, Ødum S (1990) The Greenland mountain birch zone, an introduction. Meddelelser om Grønland, Bioscience 33:3–7.

Gajewski K (1991) Représentation pollinique actuelle á la limite des arbres au Nouveau-Québec. Can J Earth Sci 28:643–648.

Gajewski K, Payette S, Ritchie JC (1993) Holocene vegetation history at the boreal-forest – shrub-tundra transition in north-western Québec. J Ecol 81:433–443.

Gajewski K (2002) Modern pollen assemblages in lake sediments from the Canadian Arctic. Arct Antarct Alp Res 34:26-32.

Golding KA, Simpson IA, Schofield JE, Edwards KJ (2011) Norse-Inuit interaction and landscape change in southern Greenland? A geochronological, pedological and palynological investigation. Geoarchaeology 26:1–31.

Grimm EC (1993) TILIA: a Program for Analysis and Display. Illinois State Museum, Springfield.

Grimm EC (2015) TGView Version 2.0.2. http://intra.museum.state.il.us/pub/grimm/. Accessed 5 January 2015

Jacobson GL, Bradshaw RHW (1981) The selection of sites for paleovegetational studies. Quat Res 16:80–96.

Jannsen CR (1973) Local and regional pollen deposition. In: Birks HJB, West RG (ed) Quaternary plant ecology, Blackwell, London, pp 31-42.

Jessen CA, Solignac S, Nørgaard-Pedersen N, Mikkelsen N, Kuijpers A, Seidenkrantz M-S (2011) Exotic pollen as an indicator of variable atmospheric circulation over the Labrador Sea region during the mid to late Holocene. J Quat Sci 26:286–296.

Kelly M, Funder S (1974) The pollen stratigraphy of late Quaternary lake sediments of South-West Greenland. Grønlands Geologiske Undersøgelse Rapport Nr. 64:1–26.

Krogh KJ (1967) Viking Greenland. National Museum, Copenhagen, Denmark.

Laegaard S (1971) In: Nørrevang A, Meyer TJ, Christensen S (ed) Danmarks natur 10: Grønland of Færøerne, Politikens Forlag, Copenhagen. pp 370-377.

Ledger PM (2013) Norse *landnám* and its impact on the vegetation of Vatnahverfi, Eastern Settlement, Greenland. Dissertation, University of Aberdeen.

Ledger PM, Edwards KJ, Schofield JE (2013) Shieling activity in the Norse Eastern Settlement: palaeoenvironment of the 'Mountain Farm', Vatnahverfi, Greenland. Holocene 23:810–822.

Ledger PM, Edwards KJ, Schofield JE (2014a) Vatnahverfi: a green and pleasant land? Palaeoecological reconstructions of environmental and land use change. Journal of the North Atlantic Special Volume 6:29–46.

Ledger PM, Edwards KJ, Schofield JE (2014b) A multiple profile approach to the palynological reconstruction of Norse landscapes in Greenland's Eastern Settlement. Quat Res 82:22–37.

Ledger PM, Edwards KJ, Schofield JE (2015) Taphonomy or signal sensitivity in palaeoecological investigations of the impact of Norse *landnám* in Vatnhaverfi, southern Greenland? Boreas 44:197–215.

Lisitsyna OV, Giesecke T, Hicks S (2011) Exploring pollen percentage threshold values as an indication for the regional presence of major European trees. Rev Palaeobot Palyno 166:311–324.

Malmros C (1994) Exploitation of local, drifted and imported wood by Vikings on the Faroe Islands. Botanical Journal of Scotland 46:552–558.

Massa C, Perren BP, Gauthier E, Bichet V, Petit C, Richard H (2012) A multiproxy evaluation of Holocene environmental change from Lake Igaliku, South Greenland. J Paleolimnol 48:241–258.

May L, Lacourse T (2012) Morphological differentiation of *Alnus* (alder) pollen from western North America. Rev Palaeobot Palyno 180:15–24.

Mayle FE, Levesque AJ, Cwynar CJ (1993) *Alnus* as an indicator taxon of the Younger Dryas cooling in eastern North America. Quaternary Sci Rev 12:295–305.

Moe D, Odland A (1992) The influence of the temperature climate on the vertical distribution of *Alnus incana* (Betulaceae) through the Holocene in Norway. Acta Botanica Fennica 144:35–49.

Morrison A (1970) Pollen diagrams from interior Labrador. Can J Botany 48:1957–1975.

Richard PJH (1994) Postglacial paleophytogeography of the eastern St. Lawrence River Watershed and the climatic signal of the pollen record. Palaeogeogr Palaeocl109:137-161.

Ritchie JC (1987) Postglacial vegetation of Canada. Cambridge University Press, Cambridge, UK.

Rousseau D-D, Schevin P, Duzer D, Cambon G, Ferrier J, Jolly D, Poulsen U (2005 Pollen transport to southern Greenland: new evidences of a late spring long distance transport. Biogeosciences discussions 2:1–19.

Rousseau D-D, Schevin P, Ferrier J, Jolly D, Andreasen T, Ascanius SE, Hendriksen S-E, Poulsen U (2008) Long-distance pollen transport from North America to Greenland in spring. J Geophysl Res 113:1–10.

Sangren P, Fredskild B (1992) Magnetic measurements recording Late Holocene man-induced erosion in S.Greenland. Boreas 20:315–331.

Sczepanek K, Tobolski K, Nalepka D (2004) *Alnus* Mill. – Alder. In: Ralska-Jasiewiczowa M, Latalowa M, Wasylikowa K, Tobolski K, Madeyska E, Wright Jr HE, Turner C (ed) Late Glacial and Holocene history of vegetation in Poland based on isopollen maps. W. Szafer Institute of Botany, Polish Academy of Sciences, Kraków, pp 47-55.

Schofield JE, Edwards KJ (2011) Grazing impacts and woodland management in Eriksfjord: *Betula*, coprophilous fungi and the Norse settlement of Greenland. Veg Hist Archaeobot 20:181–197.

Schofield JE, Edwards KJ, Christensen C (2008) Environmental impacts around the time of Norse *landnám* in the Qorlortoq valley, Eastern Settlement, Greenland. J Archaeol Sci 35:1643–1657.

Scoggan HJ (1978) The flora of Canada. Part 3 – Dicotyledoneae (Saururaceae to Violaceae). National Museum of Natural Sciences, Ottawa.

Short SK, Nichols H (1977) Holocene pollen diagrams from subarctic Labrador-Ungava: vegetational history and climatic change. Arctic Alpine Res 9:265–290.

Smith AG, Pilcher JR (1973) Radiocarbon dates and the vegetational history of the British Isles. New Phytol 72:903–914.

Sugita S (2007) Theory of quantitative reconstruction of vegetation I: pollen from large sites REVEALS regional vegetation composition. Holocene 17:229–241.

USDA NRCS (United States Department of Agriculture, Natural Resources Conservation Service) 92014) Plants database. http://plants.usda.gov/. Accessed: 15 December 2014.

Table 1 Details of the sites analysed by Fredskild (1973) and discussed in this paper. Percentages are based upon a sum of TLPS (total land pollen and spores) which includes *Alnus* but excludes other terrestrial pollen types regarded by the author as ‘exotic’.

Site	Basin size (m)	Depositional environment	*Alnus* percentages
Galium Kær A	65 x 65	Mire	A rare presence
Comarum Sø	90 x 40	Lake	A rare presence
Comarum Mose	180 x 60	Mire	A rare presence
Drepanocladus Dam	12 x 8	Kettlehole	A rare presence
Kløftsø	200 x 20	Lake	Up to 10% in the mid-Holocene, c. 2-3% thereafter
Spongilla Sø	75 x 45	Lake	5-9% in the mid-Holocene, <5% thereafter
Isoëtes Sø	90 x 25	Lake	Up to 15-20% in the mid-Holocene, c. 5% thereafter

Table 2 The pollen profiles published since 2008 that are summarised in Figure 2 and discussed in this paper. n/a = not available or unrecorded.

Site	Basin size (m)	Depositional environment	Reference
Qinngua	n/a	Small peaty hollow	Schofield and Edwards (2011)
Qorlortup Itinnera	n/a	Mire	Schofield et al. (2008)
Tasiusaq	n/a	Mire	Edwards et al. (2008)
Lake Igaliku	1150 x 450	Lake	Massa et al. (2012)
Garðar	n/a	Anthrosol	Buckland et al. (2009)
Sissarluttoq	20 x 10	Pond	Edwards et al. (2011)
Atikilleq	n/a	Anthrosol	Ledger et al. (2015)
Saqqaa	40 x 95	Mire	Ledger et al. (2014b)
Mountain Farm	110 x 46	Mire	Ledger et al. (2013)
Saqqaata Tasia	250 x 100	Lake margin	Ledger et al. (2014b)
Lake Vatnahverfi	n/a	Mire	Ledger et al. (2014b)
Nimerialik	n/a	Mire	Ledger et al. (2015)
Sandhavn	30 x 30	Mire	Golding et al. (2011)

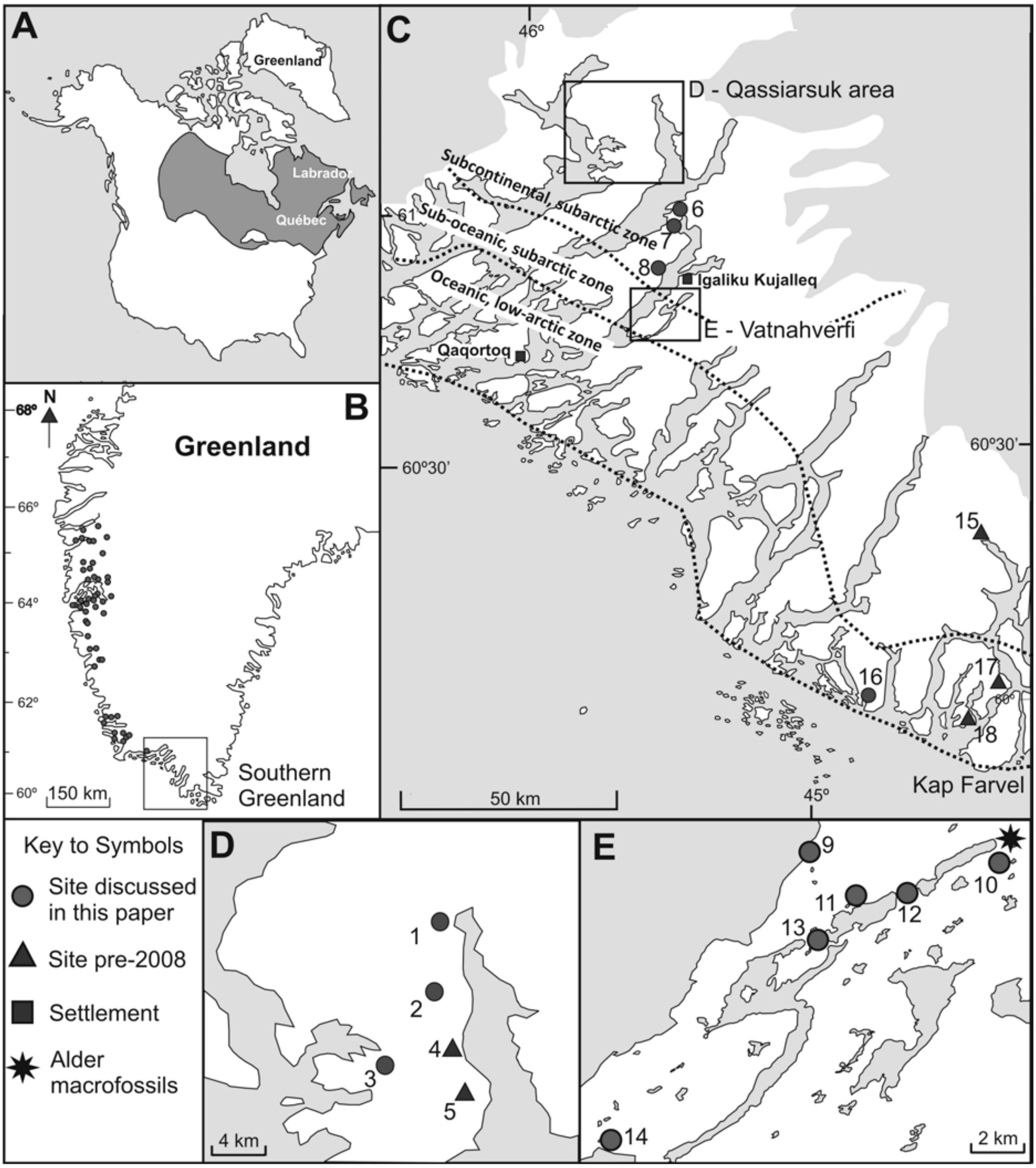

Figure 1: (A) The location of North America in relation to Greenland. The dark grey area illustrates the modern distribution of *Alnus viridis* spp. c*rispa* **(**B) the modern distribution of *Alnus crispa* (black dots) in southwestern Greenland after Feilberg (1984) and Fredskild (1996); (C) southern Greenland, illustrating the vegetation zones defined by Feilberg (1984) and the location of pollen profiles; (D) the Qassiarsuk area and the location of pollen profiles; (E) Vatnahverfi and the location of pollen profiles plus the macrofossil find of Bishop et al. (2013). Key to site numbers: 1, Qinngua; 2, Qorlortup Itinnera; 3, Tasiusaq; 4, Galium Kær A

& B; 5, Comarum Sø & Mose; 6, Lake Igaliku; 7, Igaliku/*Garðar*; 8, Sissarluttoq; 9, Atikilleq; 10, The Mountain Farm; 11, Saqqaata Tasia; 12, Saqqaa; 13, Lake Vatnahverfi; 14, Nimerialik; 15, Drepanocladus Dam; 16, Sandhavn; 17, Kløftsø; 18, Isoëtes Sø & Spongilla Sø.

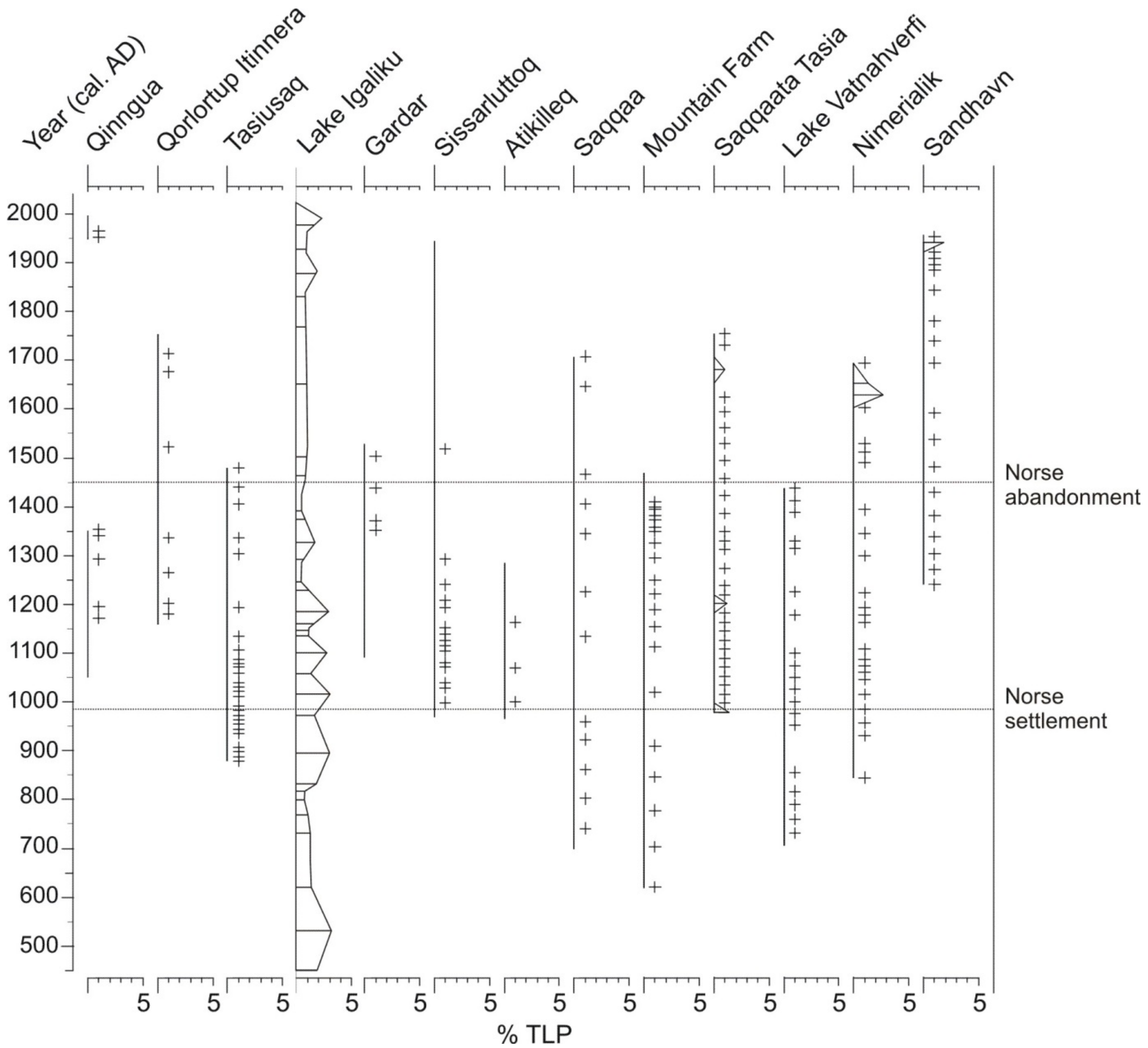

Figure 2: *Alnus* percentage pollen data for the thirteen sites published since 2008 plotted against cal. years AD. + indicates values <1% TLP. Sites are broadly arranged by their relative latitudinal positions, from north (left) to south (right). The vertical line represents the length of the analysed palynological record at the site. At Qinngua this line is broken, indicating a hiatus in the sediment column between ~AD 1350-1950. Conventional timings

for the Norse arrival (*landnám*, AD 985) and the (latest) abandonment of the Eastern Settlement (~AD 1450) are presented as horizontal lines.

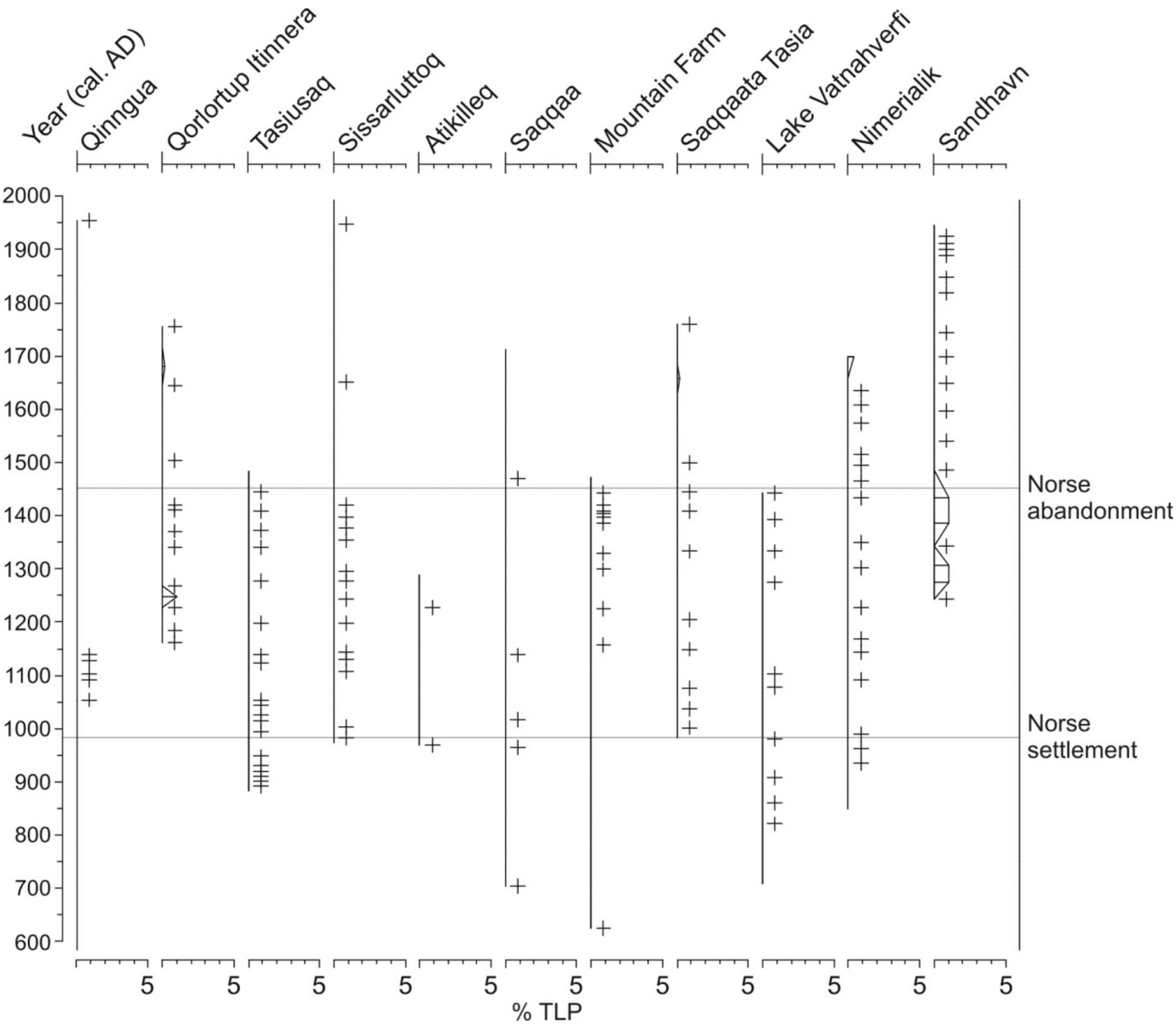

Figure 3: *Picea* percentage pollen data for the eleven sites published since 2008 plotted against cal. years AD. + indicates values <1% TLP. Sites are broadly arranged by their relative latitudinal positions, from north (left) to south (right). The vertical line represents the length of the analysed palynological record at the site. At Qinngua this line is broken, indicating a hiatus in the sediment column between ~AD 1350-1950. Conventional timings for the Norse arrival (*landnám*, AD 985) and the (latest) abandonment of the Eastern Settlement (~AD 1450) are presented as horizontal lines.