Palynological insights into global change impacts on Arctic vegetation, fire, and pollution recorded in Central Greenland ice

Authors: Sandra O Brugger[a,b], Erika Gobet[a,b], Thomas Blunier[c], César Morales-Molino[a,b,d], André F Lotter[a], Hubertus Fischer[b,e], Margit Schwikowski[b,f,g], Willy Tinner[a,b]

a) Institute of Plant Sciences, University of Bern, Switzerland
b) Oeschger Center for Climate Change Research, University of Bern, Switzerland
c) Centre for Ice and Climate, Niels Bohr Institute, University of Copenhagen, Denmark
d) Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Cadenazzo, Switzerland
e) Climate and Environmental Physics, Physics Institute, University of Bern, Switzerland
f) Paul Scherrer Institute, Villigen, Switzerland
g) Department for Chemistry and Biochemistry, University of Bern, Switzerland

sandra.bruegger@ips.unibe.ch (corresponding author)
blunier@nbi.ku.dk
erika.gobet@ips.unibe.ch
cesar.morales@ips.unibe.ch
andre.lotter@ips.unibe.ch
hubertus.fischer@climate.unibe.ch
margit.schwikowski@psi.ch
willy.tinner@ips.unibe.ch

Abstract

Arctic environments may respond very sensitively to ongoing global change, as observed during the past decades for Arctic vegetation. Only little is known about the broad-scale impacts of early- and mid-20th century industrialization and climate change on remote arctic environments. Palynological analyses of Greenland ice cores may provide invaluable insights into the long-term vegetation, fire, and pollution dynamics in the Arctic region. We present the first palynological record from a Central Greenland ice core (Summit Eurocore ’89, 72° 35' N, 37° 38' W; the location of Greenland Ice core Project GRIP) that provides novel high-resolution microfossil data on Arctic environments spanning AD 1730–1989. Our data suggest an expansion of birch woodlands after AD 1850 that was abruptly interrupted at the onset of the 20th century despite favorable climatic conditions. We therefore attribute this *Betula* woodland decline during the 20th century to anthropogenic activities such as sheep herding and wood collection in the subarctic. First signs of coal burning activities around AD 1900 coincide with the onset of Arctic coal mining. The use of coal and fire activity increased steadily until AD 1989 resulting in microscopic-size pollution of the ice sheet. We conclude that human impact during the 20th century strongly affected (sub)-Arctic environments. Moreover, ecosystems have changed through the spread of adventive plant species (e.g. *Ranunculus acris*, *Rumex*) and the destruction of sparse native woodlands. We show for the first time that optical palynology allows paleoecological reconstructions in extremely remote sites >500 km from potential sources, if adequate methods are used.

Keywords: *Betula* woodlands, coal mining, palaeoecology, pollen, microscopic charcoal, SCP (spheroidal carbonaceous particles)

1. Introduction

Central Greenland ice cores are key archives of past environmental change in the Northern Hemisphere (e.g. Blunier et al., 1993; Rasmussen et al., 2014; Seierstad et al., 2014; Vinther et al., 2010), with aerosol particles being transported to Greenland from a very wide catchment area extending from the North Atlantic and the North American continent all the way to the central Asian desert region (Schüpbach et al., 2018). The Greenland ice sheet extends over ca. 2500 km in north-south and ca. 1000 km in west-east direction with the minimum upwind distance from the Greenland summit station to the west coast being around 500 km. Hence, the area is extremely remote and exceptionally distant from local sources of biomass and fossil fuel burning. Such a setting is ideal to investigate large-scale environmental and ecological dynamics as well as the supra-regional impact of global change in the Arctic by suppressing influences of local sources.

Palaeoecological studies from such ice cores are rare and mainly rely on molecular approaches, while microfossil-based studies are lacking (De Vernal and Hillaire-Marcel, 2008; Willerslev et al., 2007). Existing Arctic palynological ice studies are restricted to pollen source areas as well as the assessment of wind directions and generally do not fully exploit the potential to reconstruct large-scale ecological and environmental dynamics (Bourgeois et al., 2000; Hicks and Isaksson, 2006; McAndrews, 1984; Short and Holdsworth, 1985). On the other hand, palynological studies on mire and lake deposits focus primarily on the local impact on vegetation of Old Norse settlements (AD 985–1500) or formerly pristine Greenland environments (Barlow et al., 1997; Bryan, 1954; Gauthier et al., 2010; Schofield and Edwards, 2011; Schofield et al., 2013; Wagner et al., 2008). Consequently, little is known about the large-scale impact of recent global change in these remote Arctic environments.

Current observations of increased fires in thawing permafrost areas and browning of vegetation raise public concern about future environmental risks in the Arctic region (Phoenix and Bjerke, 2016; Wendel, 2017). Palaeoecology may provide valuable pre-industrial base-line information and a long-term perspective on these recent observations. It may also help answering how 20th century industrialization and rapid global change are affecting sparsely inhabited and remote Arctic environments (Petit et al., 2008). For instance, studies suggest that submicron particle-bound trace elements from large-scale pollution in Europe have reached the Arctic already since the Antiquity (Hong et al. 1994; McConnell et al., 2018) while human-induced larger particle deposition may have started only with regional industrialization.

To our knowledge, we present the first palynological attempt at reconstructing vegetation, fire, and pollution history from a site in Central Greenland. Covering the past 250 years, our novel data are used to compare industrial impacts to pre-industrial conditions, and to identify triggers, processes, and mechanisms of Greenland and Arctic environmental change under global change conditions.

2. Study site and the Arctic environment

2.1. Climate and vegetation

Greenland has a vast glacial area of 1.8 million km^2 (Pfadenhauer and Klötzli, 2015) and its summit (Summit station) reaches an altitude of 3232 m a.s.l. (72° 35' N, 37° 38' W). The climate is arctic to subarctic oceanic in the southern and southwestern part that exhibits high rain- and snowfall (2200 mm weq year^{-1}; weq = water equivalent). Annual temperature amplitudes are relatively small but increase with growing continentality and in the northeastern ice-free parts of the island leesides of the main ice divide, where precipitation declines to 300 mm weq (Böcher et al., 1968; Mernild et al., 2015). Only a narrow ice-free band along the Greenland coast hosts Arctic tundra vegetation but vast upwind areas of the North American Arctic islands are covered by Arctic tundra vegetation (Fig. 1).

The Arctic tundra biome is characterized by a short growing season (1-3 summer months with a mean monthly temperature above 5° C) and long winters with extreme frost periods (temperatures below -30° C; Nentwig et al., 2004). Precipitation is not limiting for plant growth, as evapotranspiration is low (Nentwig et al., 2004). Due to the harsh climatic conditions combined with the isolated position in the North Atlantic, the modern flora in Greenland itself consists only of roughly 500 vascular plants, many of which are restricted to either the subarctic, low-arctic or high-arctic vegetation types (Bennike, 1999; Böcher et al., 1968). Subarctic vegetation is constrained to the warmest valleys in the southern and southwestern part of Greenland, where summer temperatures (>8–9°C) support thickets and woodlands including *Betula glandulosa*, *Salix glauca*, *Alnus viridis*, and the only native tree species *Betula pubescens*, growing up to 4 m height (Böcher et al., 1968). This subarctic vegetation corresponds to small patches of boreal vegetation elements within the Arctic tundra biome. Low-arctic vegetation extends up to 72° N in sheltered areas where mean July temperatures >7° C allow *Salix*-*Juniperus* shrub tundra formations (Böcher et al., 1968; Pfadenhauer and Klötzli, 2015). Finally, tall shrubs such as *B. glandulosa* and *A. viridis* are absent in the high-arctic vegetation north of ca. 69–72° N with mean July temperatures <7°C. Instead, this vegetation type is mainly composed of *Cassiope* (Ericaceae) heathlands, bogs, and grass tundra species (e.g. *Deschampsia*, *Festuca* spp., *Poa abbreviata*, *Taraxacum arcticum*, *T. pumilum*), and *Betula nana* may penetrate north to 78° N (Böcher et al., 1968). Although *B. pubescens* is the only native boreal tree in Greenland, few conifer species such as *Pinus sylvestris*, *P. contorta*, *Larix sibirica*, or *Picea glauca* endure in small plantations in southern Greenland today (Ødum, 1979).

The closest natural conifer forests occur in North America, where *Picea mariana*, *P. glauca*, *Abies balsamea*, and *Pinus banksiana* grow up to 50° N (~2000 km southwestwards from Summit; Pfadenhauer and Klötzli, 2015). American nemoboreal deciduous forests with e.g. *Acer saccharum*, *Tilia americana*, *Ulmus americana*, and *Fagus grandifolia*, are located about 3000 km southwest of Summit, while *Quercus* species are restricted to warmer temperate regions further south where the latter species are also abundant (Pfadenhauer and Klötzli, 2015).

2.2. Air mass transport to Central Greenland

The likelihood for microfossils to reach the center of the Greenland ice sheet depends strongly on the atmospheric entrainment conditions at the source, the size of the source, the atmospheric transport pathway, and the deposition en route. These conditions differ largely for more local pollen and microscopic charcoal sources at the Greenland coast compared to long-range transport of microfossils from the North American Arctic or even from Siberia.

A first isobaric 10-day back trajectory climatology for Summit showed that the vast majority of air masses reach the Greenland summit from west and southwest (Kahl et al. 1997). The overall catchment area of the trajectories is centered over the northern North American continent extending eastwards into the North Atlantic and westwards into Siberia and Northeastern Asia. As this trajectory analysis was based on isobaric wind fields, it was not able to reconstruct the three-dimensional air mass transport, which is crucial to allow for the entrainment of microfossils from the boundary layer into the free troposphere and thus, for long-range microfossil transport to Summit. A similar but isentropic back-trajectory cluster analysis was derived for the NEEM ice core site about 650 km northnorthwest of Summit (Gfeller, 2015). This analysis showed essentially the same westerly and southwesterly transport of air masses to the NEEM site as observed at Summit, indicating very similar general transport patterns for central and northern sites in Greenland with the highest density of back-trajectories crossing the Baffin Bay and the western flank of Greenland in the free troposphere for air masses within 24 hours before arrival at NEEM (Merz et al. 2014). In contrast to Kahl et al. (1997), the simulations by Gfeller (2015) allowed to reconstruct the 3D pathway of air masses and used this information to trace the trajectories to the point back in time, when they left the boundary layer for the last time (Schüpbach et al., 2018), assuming that this is the point, when the air mass was loaded with aerosol particles or larger microfossils. Although the Greenland coast was masked out as potential source area, the analysis shows clearly that the vast majority of air masses leaves the marine and terrestrial boundary layer for the last time during summer, when the pollen load should be high, and originates from the western North Atlantic and the Canadian Arctic, respectively (Schüpbach et al., 2018). In particular, only very few back-trajectories stemmed from the Baffin Bay region in the summer season. This air mass pattern combined with the often katabatic seaward flow of air in the ice-free areas of Greenland makes a direct air mass transport from the West Greenland coast relatively unlikely.

The microfossil load in air masses reaching Summit depends also on wet and dry deposition of microfossils en route, which controls its atmospheric residence time. Thus, a longer transport time and/or increased likelihood of precipitation along the transport path will deplete the microfossil load during transport and generally favor more proximal source regions such as the Greenland coast over distant sources such as the Canadian Arctic or the mid-latitude North American continent. Due to the very long transport time from the Siberian Arctic and the limited number of back-trajectories originating from this region (Gfeller, 2015; Schüpbach et al., 2018), we conclude that the impact of Siberian vegetation on the Greenland palynological signal should be negligible. The strong bias of air masses originating from the terrestrial boundary layer of the North American continent points to a bias of the microfossil origin to these regions as also supported by the occurrence of long-range transported temperate *Quercus*, *Tilia*, *Acer*, *Ulmus*, and *Fagus* pollen in our record (see Fig. 2), which cannot originate from Greenland sources. The presence of insect-pollinated *Tilia* and *Acer* is particularly surprising, given that these taxa produce low amounts of pollen (Lang, 1994).

The longer transport time from North American sources leads to a stronger depletion of the microfossil load en route compared to Greenland coastal sources. Thus, the few air masses being able to reach Summit from the Greenland coast may lead to a strong palynological signal despite the low number of air masses originating from the Greenland coastal boundary layer and the unfavorable entrainment conditions of these sources. We conclude that our palynological record from Summit in Greenland is most likely dominated by North American and Greenland sources. As we are not able to distinguish between the two based on the pollen signal, we interpret our record as a regional and supra-regional signal of environmental change in the upwind Arctic.

3. Material and Methods

The ice core was drilled during the Eurocore project in 1989 at Summit in Central Greenland (location of GRIP, Greenland Ice Core Project). Its chronology is based on layer counting in electrical conductivity, chemical data, and acid layers of volcanic eruptions (accuracy ±2 years; Blunier et al., 1993; Cachier and Pertuisot, 1994). We dedicated the remaining material with a cross section of 2.5 x 2.5 cm spanning the core depth 0–80 m (equivalent to the time span AD 1730–1989) to palynological analyses, with a gap between 58.3–61.0 m (= 11 years). Due to the isolated position of the site, the palynological analyses required large ice volumes, excessive laboratory work for sample processing, and enormous analytical efforts compared to mid-latitude high-alpine glacier sites (e.g. Brugger et al. 2018b). These site-specific properties resulted in a total of 19 samples weighing 1090–3160 g (average = 2360 g) and covering ~12 years each. Microfossil extraction followed a standard protocol for ice sample preparation (Brugger et al., 2018a) that allows maximum extraction of rare pollen with an additional 40% HF treatment to dissolve abundant dust particles.

We use pollen and spores as a proxy for vegetation and land use. The counted pollen sums ranged between 28 and 122 (average = 56) grains which is around the absolute minimum to achieve stable percentage values for environmental reconstructions (40-50 items, Heiri and Lotter, 2001). Pollen and spore identification under a light microscope at 400x magnification followed Beug (2004), McAndrews et al. (1973), Moore et al. (1991), and the reference collection at the Palaeoecology laboratory in Bern (Table S1). We separated *Betula* pollen into a tree *Betula*-type (referred to as *Betula* *alba*-type) and a shrub *Betula*-type (*Betula nana*-type; Birks, 1968; Clegg et al., 2005). We present pollen and spore data as percentages of the pollen sum with summary curves (trees, shrubs) for native Greenland arboreal taxa (Böcher et al., 1968; complete taxon list and assignment to summary curves in Table S1).

We estimated palynological richness (PRI) as a proxy for plant species richness using rarefaction analysis and the probability of interspecific encounter (PIE) as a measure for palynological evenness (Birks and Line, 1992; Hurlbert, 1971). We applied Principal Component Analysis (PCA) to the pollen percentage data based on a correlation matrix (scaling factor 2), only including native Greenland taxa, to investigate vegetation shifts in the subarctic and arctic vegetation types (following Böcher et al., 1968; see Table S1). The short gradient length of the first axis (= 1.57 standard deviation units) of a detrended correspondence analysis (DCA, detrended by segments) justifies using linear ordination methods (ter Braak and Prentice, 1988).

We used standard analysis for microscopic charcoal > 10 µm to infer regional to supra-regional fire activity (e.g. Adolf et al. 2018; Brugger et al., 2018b; Finsinger and Tinner, 2005; Tinner and Hu, 2003). Spheroidal carbonaceous particles (SCP) with a diameter > 10 µm were counted to reconstruct microscopic fossil fuel pollution (Brugger et al., 2018b; Rose, 2015). We standardized all microfossil concentrations to one liter.

4. Results and Interpretation

4.1. Pollen deposition

Pollen concentrations in the Eurocore ice record are ca. 20 grains l^{-1} in the oldest part and increase to 50 grains l^{-1} after AD 1790, except in the uppermost sample with a relatively high pollen concentration (ca. 410 grains l^{-1}; Fig. 2). This corresponds to a pollen influx along the record of ca. 0.7 grains cm^{-2} $year^{-1}$, which increases in the top sample to ca. 7 grains cm^{-2} $year^{-1}$. Pollen influx in remote Central Greenland is extremely low compared to estimates from other ice records including Arctic sites (e.g. Hicks and Isaksson, 2006). This is expected because of the long distance to the closest plants. In general, the taxonomic composition of the pollen assemblages is similar to that of other Arctic ice records with high portions of *Betula* (*B. alba*- and *B. nana*-type), Poaceae, and *Artemisia*, which are characteristic for the Arctic biome covering wide areas in the North American Arctic as well as the narrow Greenland coasts. The large portions (average = 25 %) of long-distance airborne arboreal pollen (AP) are remarkable, e.g. up to 10 % *Pinus* subgenus *Diploxylon* that may mainly derive from the North American boreal zone, although it is also growing in temperate vegetation types. This finding suggests that the main pollen source includes the Arctic with a strong influence of boreal environments (Whitmore et al., 2005) in agreement with previous trajectory analyses (Gfeller, 2015), as also documented in ice core studies from neighboring North American Arctic islands (e.g. Agassiz and Devon ice caps, Bourgeois et al., 2000; McAndrews, 1984). Compared to these sites with much smaller ice extent that are surrounded by Arctic shrub tundra, the Eurocore at Summit contains only few pollen grains of insect-pollinated plants such as Ericaceae, which comprise typical plants of the Arctic shrub tundra. This low amount of arctic insect-pollinated plants is likely the effect of the site isolation in inland ice-covered Greenland. Pollen from plants introduced e.g. during the Old Norse settlement phase in these Arctic environments (e.g. *Ranunculus acris*-type, *Rumex*; Schofield et al., 2013) indicate large-scale persistence of these taxa until modern times. Two Cerealia-type pollen grains and one *Zea mays* grain may originate from long-distance transport (e.g. North America; Thompson et al., 1999), a finding that agrees well with pollen of the temperate taxa *Quercus*, *Tilia*, *Ulmus*, *Acer*, and *Fagus* in our record.

4.2. Vegetation dynamics

Two local pollen assemblage zones (LPAZ) reflect the vegetation development. LPAZ Sum-1 (AD 1730–1900) consists of 50 to 60 % arboreal pollen (AP, sum of trees and shrubs), suggesting the prevalence of open habitats such as arctic tundra during the period AD 1730–1900 in the pollen catchment. Pollen of the only native Greenland tree (*Betula alba*-type) increases to 30 % and shrub pollen (e.g. *Alnus viridis* type, *Betula nana* type, *Salix*, and *Juniperus)* slightly rises to 25 % between AD 1850 and 1900, indicating a spread of subarctic woodlands and thickets (Fig. 2). After AD 1900 (LPAZ Sum-2, AD 1900–1989), non-arboreal pollen (NAP, herbs) expand (e.g. *Artemisia*, *Ambrosia*, other Asteroideae, Poaceae), while *Betula alba*-type, *Alnus viridis*-type, and *Betula nana*-type as well as fern spores decrease, suggesting that open herb and grass tundra replaced scattered subarctic woodlands and thickets. Pollen percentages of shrubs that were probably growing in the Arctic tundra remain stable (e.g. *Juniperus*) or marginally increase (e.g. *Salix*). Finally, the pollen record shows that *Betula* woodlands partly recovered around AD 1960(supported by increasing influx values) and then declined to a minimum around AD 1990 (Fig. 2).

Pollen richness (PRI = 15–18, based on the pollen sum of 28; Fig. 2) is relatively high and remains stable over the past 250 years. The pollen spectra at Summit are markedly influenced by continuous and diverse long-distance pollen deposition from boreal and nemoboreal tree taxa such as e.g. *Quercus*, *Tilia*, *Ulmus*, *Acer*, and *Fagus* deriving from >2000 km distance. This long-distance pollen hampers the regional subarctic-arctic diversity estimation, an effect, which was also recorded in calibration studies using surface soil samples (Felde et al., 2016). Pollen evenness (PIE = 0.9–0.95; Fig. 2) remains stable and relatively high due to the co-occurrence of several major taxa that dominate along the record (e.g. Poaceae, *Artemisia*, *Betula alba*-type). The stable diversity estimation agrees with local richness estimations from a southern Greenland peat deposit that suggests no local richness trend during the past centuries (Schofield and Edwards, 2011).

The sample distribution on PCA axes 1 (33.2 %) and 2 (22.5 % variance explained, Fig. 3), separates samples from Sum-1 and Sum-2 along axis 1, supporting the LPAZ boundary. The ordination splits taxa indicative of boreal to subarctic shrub- and woodlands (e.g. *Betula alba*-type, *Alnus viridis*-type, *Cornus suecica*-type) from arctic taxa that grow on wet (e.g. *Artemisia*, *Salix*, Cyperaceae, *Anemone*-type) or dry soils (e.g. Poaceae, Chenopodiaceae; Schofield and Edwards, 2011). Despite the clear trends with regard to taxa and sample grouping, caution is needed when interpreting the ordination data as low pollen counts may influence PCA results (Heiri and Lotter, 2001).

4.3. Fire and fossil fuel combustion

Microscopic charcoal concentration (average ca. 700 particles l^{-1} along the record) and influx (average ca. 9 particles cm^{-2} $year^{-1}$) are extremely low compared to other Arctic ice records (ca. 200 particles cm^{-2} $year^{-1}$ at Lomonosovfonna; Hicks and Isaksson, 2006) or to Greenland sedimentary records (ca. 500 particles cm^{-2} $year^{-1}$; Schofield and Edwards, 2011) as a result of the large distance to the source areas. The microscopic charcoal influx suggests two periods of enhanced regional fire activity around AD 1790 and after AD 1970. Considering the predominant westerly wind direction (Steffen and Box, 2001), potential sources include peatland fires on the Greenland coast, the North American Arctic or more likely boreal forest fires in North America (Fischer et al., 2015). SCP deposition at Summit starts around AD 1880 and rises steadily after AD 1900, suggesting increased atmospheric pollution from regional and/or long-distance fossil fuel burning (e.g. coal; Rose, 2015).

5. Discussion

5.1. Fire activity and fossil fuel burning in the Arctic

Summit recorded two major peaks in fire activity during the past 300 years, around AD 1790 and after 1970. The first peak correlates with increased fire activity documented at the boreal forest-tundra ecotone in Alaska, possibly caused by reduced precipitation during the Little Ice Age (LIA; Tinner et al., 2008) and was recorded in the black carbon (BC) record from Eurocore (Cachier and Pertuisod, 1994). On the other hand, BC, ammonium, and levoglucosan-based fire reconstructions from the northwestern Greenland NEEM ice core suggest minimum fire activity between AD 1600 and 1750 (Legrand et al., 2016; Zennaro et al., 2014). The recent fire activity increase corresponds to rising fire severity in the North American boreal forests in the course of the 20th century, attributed to both man-set fires and natural ignition (Calef et al., 2017; Kelly et al., 2013; Legrand et al., 2016; Soja et al., 2007; Veraverbeke et al., 2017). Thus, either regional fire activity trends followed similar trajectories or fire activity at Summit is reflecting distant forest fires (Thomas et al., 2017).

SCP maximum values in the Eurocore remain about 50 times lower than in other ice records such as Lomonosovfonna, Svalbard (ca. 0.5 vs. ca. 40 particles cm^{-2} $year^{-1}$; Hicks and Isaksson, 2006). This pronounced difference is a consequence of the large distance (> 500 km) between the Eurocore drilling site and potential source areas. In contrast, three coal-fired power stations in Svalbard are located only ca. 70 km from Lomonosovfonna glacier (Hicks and Isaksson, 2006), potentially dominating its SCP record. The onset of SCP pollution at Summit at ca. AD 1880 is concurrent with the start of the SCP increase in Nunatak lake in Western Greenland (Rose, 2015) and in Lomonosovfonna glacier in Svalbard (Hicks and Isaksson, 2006) and the rise of BC in Greenland records (McConnell et al. 2007; Fig. 4). The synchronous onset of SCP deposition likely originated from widespread Arctic coal mining activities during the late-19th and early 20th century. Historical sources give evidence of coal mining in Nova Scotia (Canada) already since AD 1800, in Greenland since AD 1890, in Svalbard since AD 1907, whereas coal based-ore smelting started after AD 1911 in Greenland (Patterson, 1877; Kosack, 1967; National Museum of Denmark). More generally, our SCP record follows the progressive fossil fuel burning of the 20th century, globally observed in many sedimentary SCP records (see Fig. 4; Rose, 2015).

The increasing long-term trends of microscopic charcoal-inferred forest fire and SCP-inferred fossil fuel burning activity at Summit contrasts with BC and vanillic acid (VA)-based reconstructions from Greenland that suggest maximum fossil fuel pollution at the beginning of the 20th century, mainly attributed to coal burning (McConnell et al., 2007). Technical advances, which reduced emissions to the atmosphere served as an explanation for the early decline of BC (e.g. D4 record, Fig. 4; McConnell et al., 2007). In contrast to our microscopic proxies, these BC records mainly capture submicron particles with a long residence time in the atmosphere and thus likely reflect a continental to northern hemispheric catchment, including the industrialized countries (McConnell et al., 2007). Because of the larger size of microscopic particles (> 10 µm), reconstructed pollution and fires may primarily come from upwind American Arctic sources, as revealed by continental calibration (Adolf et al., 2018) and global modelling efforts (Gilgen et al., 2018). These contrasting trends are interesting because they suggest that despite declining northern hemispheric trends, microscopic-particle pollution in sensitive Arctic environments probably increased as late as during the 1980s. We hypothesize that in recent decades SCP may have also derived from increasing oil combustion, possibly including gasoline (Rose, 2015). This is supported by reconstructed lead (Pb)-pollution, which culminated in the Arctic in AD 1960–1980 and partly derived from gasoline consumption (Bindler et al., 2001; McConnell et al., 2007).

5.2. Anthropogenic footprint on Greenland vegetation

The Medieval Norse culture in Greenland had a strong impact on Subarctic birch-willow shrublands around settlements that persisted until they were abandoned ca. AD 1350–1450 (Barlow et al., 1997; Berglund, 1986). The subsequent recovery of these shrub- and woodlands implies a resilience of Arctic vegetation to local human disturbance similar to observed vegetation recoveries after moderate anthropogenic impact of Neolithic settlements in e.g. European temperate forests (e.g. Rey et al., 2017). However, our palynological record from Summit suggests that the rapid colonization by alien plants (Bennike, 1999) introduced by European settlers to the North American Arctic and Greenland such as *Rumex* or *Ranunculus acris* was irreversible, as documented by the supra-regional pollen signal three centuries later.

Tree *Betula* may form temperature-controlled tree lines (Hoch and Körner, 2003; Wieser et al., 2014) in Greenland and in other Arctic areas (Anschlag et al., 2008; Hobbie and Chapin III, 1998; Karlsson and Nordell, 1996). After the termination of the LIA at ca. AD 1850 (Fischer et al., 1998; Kaufman et al., 2009), rising temperatures increased shrub growing rates in East Greenland and the Alaskan Arctic (Büntgen et al., 2015; Myers-Smith and Hik, 2018; Sturm et al., 2001), and allowed re-expansion of boreal forests in Alaska (Tinner et al., 2008) and elsewhere in the Arctic (Kullman and Öberg, 2009; Lescop-Sinclair and Payette, 1995; McDonald et al., 2008). In agreement, our record suggests birch woodland expansions (Figs. 2, 4). However, these woodland expansions ended ca. AD 1910, when favorable climatic conditions with rising temperatures in the course of the 20th century should have further promoted expansions of Subarctic birch woodlands (Fredskild, 1991; Fig. 4). This departure between temperature and vegetation dynamics coincided with the onset of Arctic coal mining activities (Hicks and Isaksson, 2006; Kosack, 1967). We therefore speculate that increasing human impact may have contributed to the reduction of sparse woodlands in the

Arctic during the 20th century. *Betula pubescens* woods are currently restricted to climatically mild conditions as e.g. in Southern Greenland valleys, which are attractive for human settlements (Kosack, 1967). Although substantial portions of energy consumption were covered by coal rather than timber burning in the Arctic, birch woodlands potentially provided an additional natural resource exploitable for various purposes as e.g. for constructions and fencing for cattle since natural timber sources are limited, and apart from birch trees and several shrub species, wood is largely restricted to drift wood from the ocean (Alix, 2005). Thus, in these northernmost ecosystems human impact during the 20th century partly converted quasi-natural to anthropogenic vegetation, despite the remoteness and climatically challenging natural conditions of the harsh environments (Fig. 4). Given that the birch species involved is a strong pioneer, *Betula* woodlands may re-expand rapidly in the future, e.g. through the establishment of woodland conservation areas (a protection area is already implemented in the Qinngua valley; Austrheim et al., 2008; Ross et al., 2016).

6. Conclusions

Our palynological record from Central Greenland reveals that increasing anthropogenic activities at the beginning of the 20th century markedly affected Arctic environments. Ecosystem modification included the spread of adventive plants and subarctic deforestation as well as pollution from both, fossil fuel burning and increasing forest fires. Land use and pollution may contribute to alter even most remote Arctic ecosystems. Specifically, pollution of ice through dark microscopic particles might become of growing importance given the recent increase of fire activity in Greenland (Wendel, 2017). “Blackening” of pure Greenland snow and outcropping ice due to deposition of black particles may accelerate climate-warming feedbacks, thus reinforcing ice melting and fire risk. This study illustrates for the first time that Central Greenland ice core records have a high potential for the reconstruction of long-term high-resolution environmental dynamics in the Arctic. Palaeoecological ice studies covering longer past periods than Eurocore ‘89 and reaching modern time may further constrain the long-term triggers, processes, and mechanisms of rapid environmental change in the Arctic.

7. Data accessibility

All data will be deposited in the Neotoma database (https://www.neotomadb.org)

8. Acknowledgments

We are grateful to the Eurocore ’89 drilling team at Summit and to Alexander Bolland for assistance with the ice transport from Copenhagen to Bern. We thank the two anonymous reviewers for their suggestions that improved the manuscript. We acknowledge the Sinergia project *Paleo fires from high-alpine ice cores* funded by the Swiss National Science Foundation (SNF grant 154450).

9. References

Adolf C, Wunderle S, Colombaroli D, Weber H, Gobet E, Heiri O, van Leeuwen JFN, Bigler C, Connor SE, Gałka m, La Mantia T, Makhortykh S, Svitavská-Svobodová H, Vannière B, Tinner W (2018) The sedimentary and remote-sensing reflection of biomass burning in Europe. *Global Ecology and Biogeography* 27(2), 199-212.

Alix C (2005) Deciphering the impact of change on the driftwood cycle: contribution to the study of human use of wood in the Arctic. *Global and Planetary Change* 47(2-4) 83-98.

Anderson PM, Bartlein PJ, Brubaker LB et al. (1991) Vegetation-pollen-climate relationships for the arcto-boreal region of North America and Greenland. *Journal of Biogeography* 565-582.

Anschlag K, Broll G and Holtmeier FK (2008) Mountain birch seedlings in the treeline ecotone, subarctic Finland: variation in above-and below-ground growth depending on microtopography. *Arctic, Antarctic, and Alpine Research* 40(4) 609-616.

Austrheim G, Asheim LJ, Bjarnason G et al. (2008) Sheep grazing in the North-Atlantic region—A long term perspective on management, resource economy and ecology. *Rapport zoologisk serie* 3 86.

Barlow LK, Sadler JP, Ogilvie AE et al. (1997) Interdisciplinary investigations of the end of the Norse Western Settlement in Greenland. *The Holocene* 7(4) 489-499.

Bennike O (1999) Colonisation of Greenland by plants and animals after the last ice age: a review. *Polar Record* 35(195) 323-336.

Berglund J (1986) The decline of the Norse settlements in Greenland. *Arctic Anthropology* 109-135.

Beug HJ (2004) *Leitfaden der Pollenbestimmung für Mitteleuropa und angrenzende Gebiete*. Pfeil.

Bindler R, Renberg I, Anderson NJ et al. (2001) Pb isotope ratios of lake sediments in West Greenland: inference on pollution sources. *Atmospheric Environment* 35 4675-4685.

Birks HJB and Line JM (1992) The use of rarefaction analysis for estimating palynological richness from Quaternary pollen-analytical data. *The Holocene* 2(1) 1-10.

Birks HJB (1968) The identification of Betula nana pollen. *New Phytologist* 67(2), 309-314.

Blunier T, Chappellaz J, Schwander J et al. (1993) Atmospheric methane, record from a Greenland ice core over the last 1000 years. *Journal of Geophysical Research* 20 2219-2222.

Böcher TW, Holmen K and Jakobsen K (1968) *The flora of Greenland*. Haase.

Bourgeois JC, Koerner RM, Gajewski K et al. (2000) A Holocene ice-core pollen record from Ellesmere Island, Nunavut, Canada. *Quaternary Research* 54(2) 275-283.

Brugger SO, Gobet E, Schanz FR et al. (2018a) A quantitative comparison of microfossil extraction methods from ice cores. *Journal of Glaciology* 64(245) 432-442

Brugger SO, Gobet E, Sigl M et al. (2018b) Ice records provide new insights into climatic vulnerability of Central Asian forest and steppe communities. *Global and Planetary Change* 169, 188-201.

Bryan MS (1954) Interglacial pollen spectra from Greenland. *Danm Geol Unders II*, 80 65.

Büntgen U, Hellmann L, Tegel W et al. (2015) Temperature-induced recruitment pulses of Arctic dwarf shrub communities. *Journal of Ecology* 103(2) 489-501.

Cachier and Pertuisot (1994) Particulate carbon in Arctic ice. *Analusis Magazine* 22(7).

Calef MP, Varvak A and McGuire AD (2017) Differences in Human versus Lightning Fires between Urban and Rural Areas of the Boreal Forest in Interior Alaska. *Forests* 8(11) 422.

Clegg BF, Tinner W, Gavin DG et al. (2005) Morphological differentiation of Betula (birch) pollen in northwest North America and its palaeoecological application. *The Holocene* 15(2) 229-237.

De Vernal A and Hillaire-Marcel C (2008) Natural variability of Greenland climate, vegetation, and ice volume during the past million years. *Science* 320(5883) 1622-1625.

Felde VA, Peglar SM, Bjune AE et al. (2016) Modern pollen–plant richness and diversity relationships exist along a vegetational gradient in southern Norway. *The Holocene* 26(2), 163-175.

Finsinger W and Tinner W (2005) Minimum count sums for charcoal concentration estimates in pollen slides: accuracy and potential errors. *The Holocene* 15(2) 293-297.

Fischer H, Werner M, Wagenbach D et al. (1998) Little Ice Age clearly recorded in northern Greenland ice cores. *Geophysical Research Letters* 25(10) 1749-1752.

Fischer H, Schüpbach S, Gfeller G et al. (2015) Millennial changes in North American wildfire and soil activity over the last glacial cycle. *Nature Geosciences* 8 723-727.

Frechette B, de Vernal A, Richard PJ (2008) Holocene and last interglacial cloudiness in eastern Baffin Island, Arctic Canada. *Canadian Journal of Earth Sciences* 45(11) 1221-1234.

Fredskild B (1991) The genus Betula in Greenland-Holocene history, present distribution and synecology. *Nordic Journal of Botany* 11(4) 393-412.

Gauthier E, Bichet V, Massa C et al. (2010) Pollen and non-pollen palynomorph evidence of medieval farming activities in southwestern Greenland. *Vegetation History and Archaeobotany* 19(5-6) 427-438.

Gfeller G (2015) What controls chemical aerosol signals in Greenland ice cores. PhD thesis, University of Bern.

Gilgen A, Adolf C, Brugger SO et al. (2018) Implementing microscopic charcoal particles into a global aerosol–climate model. *Atmospheric Chemistry and Physics* 18(16), 11813-11829.

Heiri O and Lotter AF (2001) Effect of low count sums on quantitative environmental reconstructions: an example using subfossil chironomids. *Journal of Paleolimnology* 26(3) 343-350.

Hicks S and Isaksson E (2006) Assessing source areas of pollutants from studies of fly ash, charcoal, and pollen from Svalbard snow and ice. *Journal of Geophysical Research: Atmospheres* 111(D2) 1-9.

Hobbie SE and Chapin III FS (1998) An experimental test of limits to tree establishment in Arctic tundra. *Journal of Ecology* 86(3) 449-461.

Hoch G and Körner C (2003) The carbon charging of pines at the climatic treeline: a global comparison. *Oecologia* 135(1) 10-21.

Hong S, Candelone JP, Patterson CC et al. (1994) Greenland ice evidence of hemispheric lead pollution two millennia ago by Greek and Roman civilizations. *Science* 265(5180) 1841-1843.

Hurlbert SH (1971) The nonconcept of species diversity: a critique and alternative parameters. *Ecology* 52(4) 577-586.

Kahl JDW, Martinez DA, Kuhns H (1997) Air mass trajectories to Summit Greenland: A 44-year climatology and some episodic events. *Journal of Geophysical Research:* Oceans 102, 26861-26875.

Karlsson PS and Nordell KO (1996) Effects of soil temperature on the nitrogen economy and growth of mountain birch seedlings near its presumed low temperature distribution limit. *Ecoscience* 3(2) 183-189.

Kaufman DS, Schneider D P, McKay NP et al. (2009) Recent warming reverses long-term Arctic cooling. *Science* 325(5945), 1236-1239.

Kelly R, Chipman ML, Higuera PE et al. (2013) Recent burning of boreal forests exceeds fire regime limits of the past 10,000 years. *Proceedings of the National Academy of Sciences* 110(32) 13055-13060.

Kosack HP (1967) *Die Polarforschung*. Vieweg.

Kullman L and Öberg L (2009) Post-Little Ice Age tree line rise and climate warming in the Swedish Scandes: a landscape ecological perspective. *Journal of Ecology* 97(3), 415-429.

Lang G (1994*) Quartäre Vegetationsgeschichte Europas: Methoden und Ergebnisse*. Gustav Fischer, Jena

Legrand M, McConnell J, Fischer H et al. (2016) Boreal fire records in Northern Hemisphere ice cores: a review. *Climate of the Past* 12 2033-2059.

Lescop-Sinclair K and Payette S (1995) Recent advance of the arctic treeline along the eastern coast of Hudson Bay. *Journal of Ecology* 929-936.

McAndrews JH (1984) Pollen analysis of the 1973 ice core from Devon Island Glacier, Canada. *Quaternary Research* 22(1) 68-76.

McAndrews JH, Berti AA and Norris G (1973) *Key to the Quaternary pollen and spores of the Great Lakes region*. Royal Ontario Museum

McConnell JR, Edwards R, Kok GL et al. (2007) 20th-century industrial black carbon emissions altered arctic climate forcing. *Science* 317(5843) 1381-1384.

McConnell JR, Wilson AI, Stohl A et al. (2018) Lead pollution recorded in Greenland ice indicates European emissions tracked plagues, wars, and imperial expansion during antiquity. *Proceedings of the National Academy of Sciences* 201721818.

MacDonald GM, Kremenetski KV and Beilman DW (2008) Climate change and the northern Russian treeline zone. *Philosophical Transactions of the Royal Society of London B: Biological Sciences* 363(1501), 2283-2299.

Mernild SH, Hanna E, McConnell JR et al. (2015) Greenland precipitation trends in a long-term instrumental climate context (1890–2012): evaluation of coastal and ice core records. *International Journal of Climatology* 35(2) 303-320.

Merz N, Gfeller G, Born A et al. (2014) Influence of ice sheet topography on Greenland precipitation during the Eemian interglacial. *Journal of Geophysical Research: Atmospheres*

119(18) 10-749.

Moore PD, Webb JA and Collison ME (1991) *Pollen analysis*. Oxford, Blackwell scientific publications.

Myers-Smith IH and Hik DS (2018) Climate warming as a driver of tundra shrubline advance. *Journal of Ecology* 106(2) 547-560.

National Museum of Denmark: *Greenland in the late 19th-early 20th century* (Th. N. Krabbe Collection)

Nentwig W, Bacher S, Beierkuhnlein C et al. (2004). *Ökologie*. Spektrum.

Ødum S (1979) Actual and potential tree-line in the North Atlantic region, especially in Greenland and the Faroes. *Ecography* 2(4) 222-227.

Patterson G (1877) *A history of the county of Pictou, Nova Scotia*. Montreal, Dawson Brothers. 471 pp.

Petit RJ, Hu FS and Dick CW (2008) Forests of the Past: A Window to Future Changes. *Science* 1155457(1450), 320.

Pfadenhauer JS and Klötzli FA (2015) *Vegetation der Erde: Grundlagen, Ökologie, Verbreitung.* Berlin, Springer.

Phoenix GK and Bjerke JW (2016) Arctic browning: extreme events and trends reversing arctic greening. *Global Change Biology* 22(9) 2960-2962.

Rasmussen SO, Bigler M, Blockley SP et al. (2014) A stratigraphic framework for abrupt climatic changes during the Last Glacial period based on three synchronized Greenland ice-core records: refining and extending the INTIMATE event stratigraphy. *Quaternary Science Reviews* 106 14-28.

Rey F, Gobet E, van Leeuwen JFN et al. (2017) Vegetational and agricultural dynamics at Burgäschisee (Swiss Plateau) recorded for 18,700 years by multi-proxy evidence from partly varved sediments. *Vegetation History and Archaeobotany* 26(6) 571-586.

Rose NL (2015) Spheroidal carbonaceous fly ash particles provide a globally synchronous stratigraphic marker for the Anthropocene. *Environmental Science & Technology* 49(7) 4155-4162.

Ross LC, Austrheim G, Asheim LJ et al. (2016). Sheep grazing in the North Atlantic region: A long-term perspective on environmental sustainability. *Ambio* 45(5) 551-566.

Schofield J E, Edwards KJ, Erlendsson E and Ledger PM (2013) Palynology supports 'Old Norse'introductions to the flora of Greenland. *Journal of Biogeography* 40(6) 1119-1130.

Schofield JE and Edwards KJ (2011) Grazing impacts and woodland management in Eriksfjord: Betula, coprophilous fungi and the Norse settlement of Greenland. *Vegetation History and Archaeobotany* 20(3) 181-197.

Schüpbach S, Fischer H, Bigler M et al. (2018) Greenland records of aerosol source and atmospheric lifetime changes from the Eemian to the Holocene. *Nature Communications* doi:10.1038/s41467-41018-03924-41463

Seierstad IK, Abbott PM, Bigler M et al. (2014) Consistently dated records from the Greenland GRIP, GISP2 and NGRIP ice cores for the past 104 ka reveal regional millennial-scale δ18O gradients with possible Heinrich event imprint. *Quaternary Science Reviews* 106 29-46.

Short SK and Holdsworth G (1985) Pollen, Oxygen Isotope Content and Seasonally in an Ice Core from the Penny Ice Cap, Baffin Island. *Arctic* 214-218.

Soja AJ, Tchebakova NM, French NH et al. (2007) Climate-induced boreal forest change: predictions versus current observations. *Global and Planetary Change* 56(3-4) 274-296.

Steffen K and Box J (2001) Surface climatology of the Greenland ice sheet: Greenland Climate Network 1995–1999. *Journal of Geophysical Research: Atmospheres* 106(D24) 33951-33964.

Sturm M, Racine C and Tape K (2001) Climate change: increasing shrub abundance in the Arctic. *Nature* 411(6837) 546.

Ter Braak CJF and Prentice IC (1988) A theory of gradient analysis. *Advances in ecological research* 18 271-317.

Thomas JL, Polashenski CM, Soja AJ et al. (2017) Quantifying black carbon deposition over the Greenland ice sheet from forest fires in Canada. *Geophysical Research Letters* 44(15) 7965-7974.

Thompson RS, Anderson KH and Bartlein PJ (1999) *Atlas of relations between climatic parameters and distributions of important trees and shrubs in North America*. US Department of the Interior, US Geological Survey.

Tinner W and Hu FS (2003) Size parameters, size-class distribution and area-number relationship of microscopic charcoal: relevance for fire reconstruction. *The Holocene* 13(4) 499-505.

Tinner W, Bigler C, Gedye S et al. (2008) A 700-year paleoecological record of boreal ecosystem responses to climatic variation from Alaska. *Ecology* 89(3) 729-743.

Veraverbeke S, Rogers BM, Goulden ML et al. (2017) Lightning as a major driver of recent large fire years in North American boreal forests. *Nature Climate Change* 7(7) 529.

Vinther BM, Jones PD, Briffa KR et al. (2010) Climatic signals in multiple highly resolved stable isotope records from Greenland. *Quaternary Science Reviews* 29(3) 522-538.

Wagner B, Bennike O, Bos JA et al. (2008) A multidisciplinary study of Holocene sediment records from Hjort Sø on Store Koldewey, Northeast Greenland. *Journal of Paleolimnology* 39(3) 381-398.

Wendel J (2017) Greenland fires ignite climate change fears. *Earth & Space Science News Eos* 98. Doi: 10.1029/2017EO079715.

Whitmore J, Gajewski K, Sawada M et al. (2005) Modern pollen data from North America and

Greenland for multi-scale paleoenvironmental applications. *Quaternary Science Reviews* 24(16) 1828-1848.

Wieser G, Holtmeier, FK and Smith WK (2014) Treelines in a changing global environment. In: *Trees in a changing environment*. Dordrecht, Springer.

Willerslev E, Cappellini E, Boomsma W et al. (2007) Ancient biomolecules from deep ice cores reveal a forested southern Greenland. *Science* 317(5834) 111-114.

Zennaro P, Kehrwald N, McConnell JR et al. (2014) Fire in ice: two millennia of boreal forest fire history from the Greenland NEEM ice core. *Climate of the Past* 10(5) 1905-1924.

10. Figures

Figure 1 Map of Greenland and northwest America. Vegetation zones modified from Frechette et al. (2008) and Pfadenhauer and Klötzli (2015). Numbers indicate the drilling location of the Eurocore’89 at Summit and selected palynological records in the Arctic. Ice cores from 1: Agassiz ice cap (Bourgeois et al., 2000), 2: Devon island (McAndrews, 1984), 3: Baffin island (Short and Holdsworth, 1985), D4 (e.g. McConnell et al., 2007). Sedimentary palaeoecological sites from A: Eastern Norse settlement around Igaliku lake (e.g. Schofield et al., 2013), B: Western Norse settlement (e.g. Barlow et al., 1997), C: Nunatak lake (Rose, 2015). Subarctic vegetation is composed of boreal vegetation elements in arctic environments, not shown in map. The map does not display smaller ice caps in the Arctic as e.g. Devon, Baffin or Agassiz.

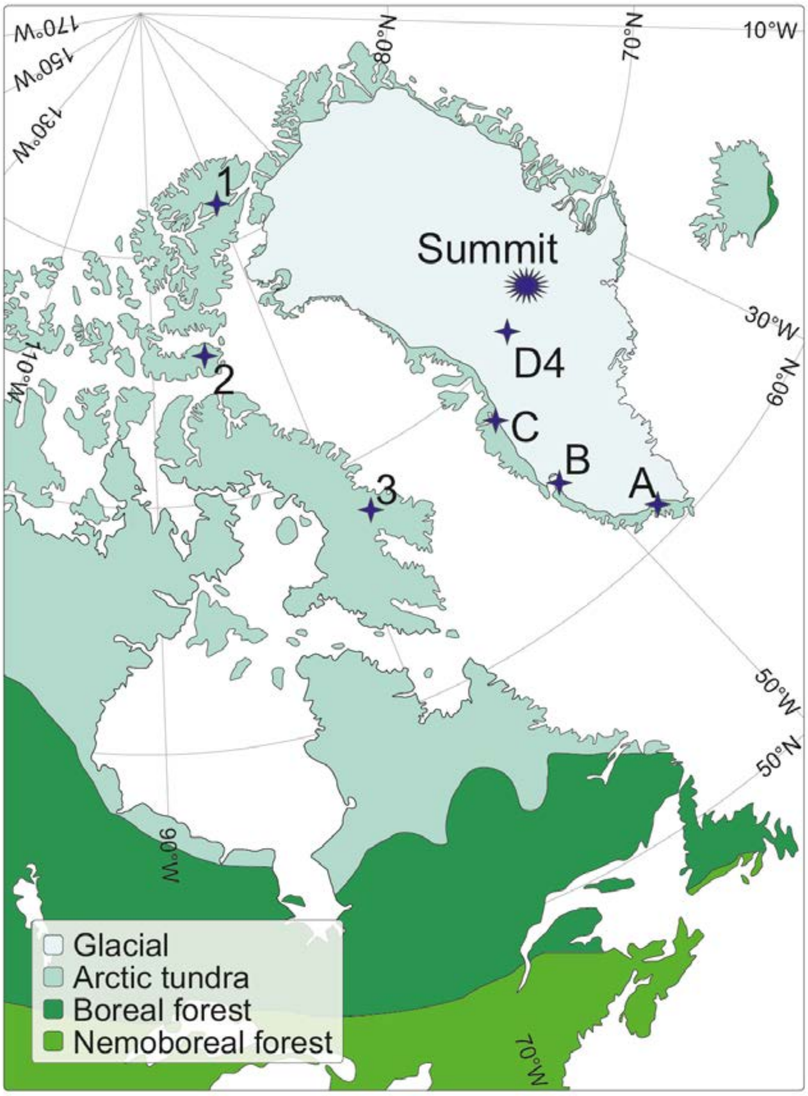


Figure 2 Pollen diagram of Summit Eurocore'89 (Greenland) shows pollen percentages of selected pollen types and fern spores based on the terrestrial pollen sum with indication of taxa growing in Greenland including introduced taxa by the Old Norse (adventive taxa) and taxa that are currently not growing in Greenland (following Böcher et al., 1968). Portion of total Greenland native trees and shrubs from all arboreal pollen in the main diagram. AP = arboreal pollen, NAP = non-arboreal pollen, t. = type. Concentration curves for pollen, microscopic charcoal, and spheroidal carbonaceous particles (SCP) in particles per liter (particles l^{-1}), influx curves for microscopic charcoal and total pollen per area per year (particles cm^{-2} $year^{-1}$), and total terrestrial pollen sum. Hollow curves = 10x exaggeration. Diversity estimation (Hurlbert, 1971) based on a minimum pollen sum of 28 for pollen richness (PRI) and evenness index (PIE). LPAZ = visually delimited local pollen assemblage zones.

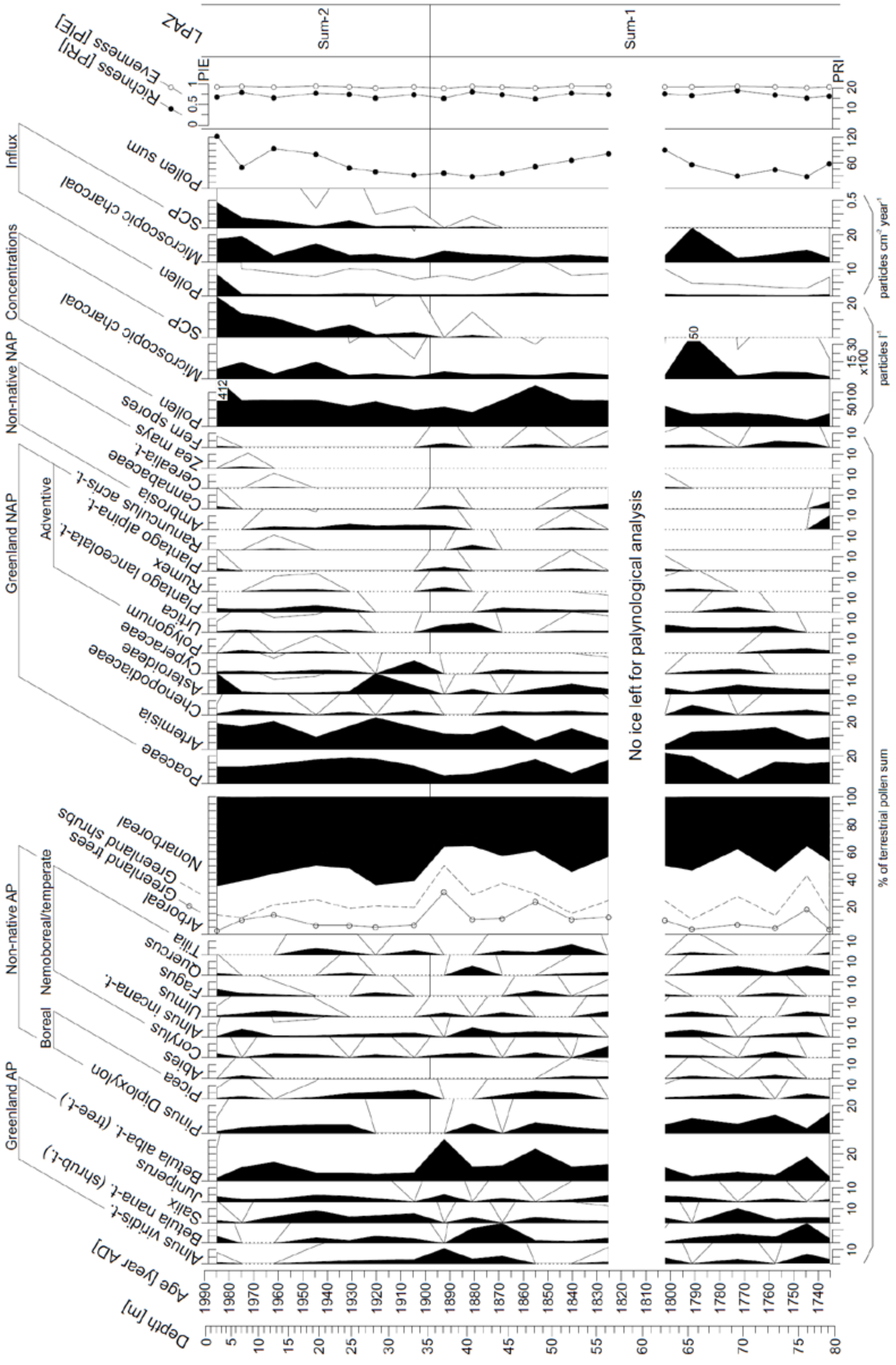


Figure 3 Principal Component Analysis (PCA) for the Summit Eurocore'89 (Greenland) pollen percentage record. Only taxa growing in Greenland (following Böcher et al., 1968) are included in the dataset. Graph shows selected pollen taxa and sample scores grouped according to the optically defined local pollen assemblage zones (Sum-1 and Sum-2). t. = pollen-type. *Betula alba*-type = tree-type *Betula*, *Betula nana*-t. = shrub-type *Betula*.

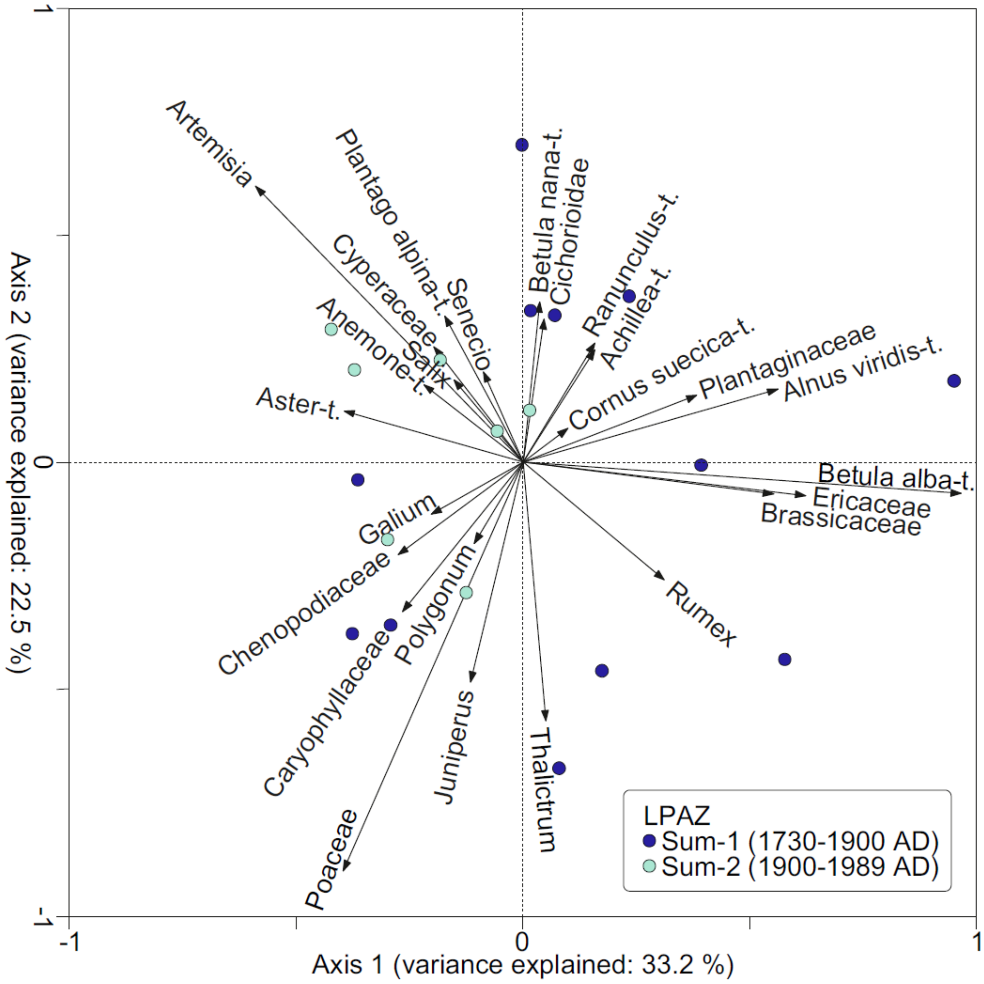
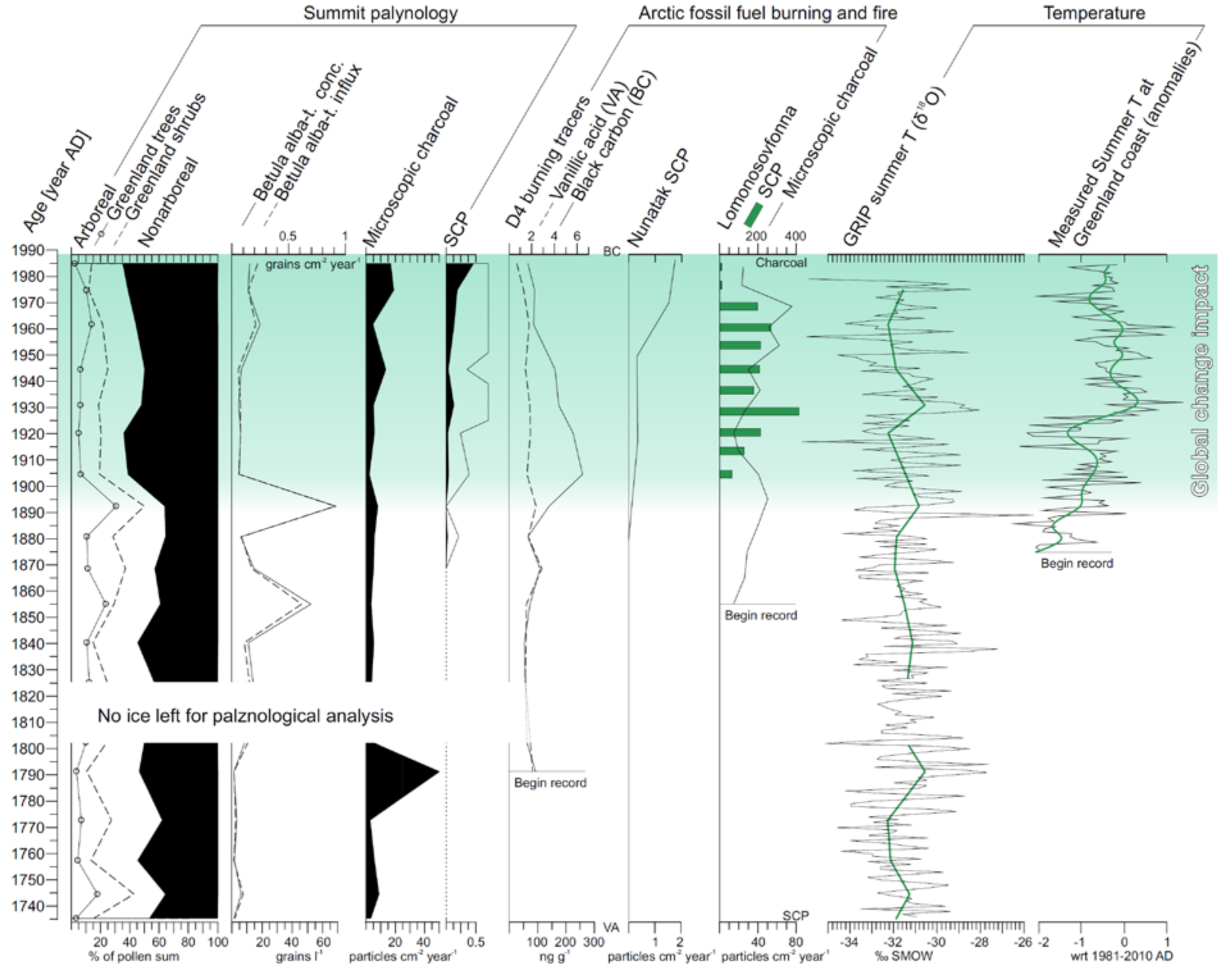


Figure 4 Comparison of Summit Eurocore ’89 palynological record (pollen percentages, *Betula alba*-type concentration and influx, microscopic charcoal influx, and SCP =spheroidal carbonaceous particles influx) with independent burning and temperature records. Black carbon and vanillic acid records from the D4 site (pooled to the resolution of the palynological record; McConnell et al., 2007), SCP record from Nunatak lake in Western Greenland (Rose, 2015), Svalbard palynological burning records (SCP and microscopic charcoal influx; Hicks and Isaksson, 2006), GRIP summer temperature (δ^{18}O in 1 year resolution and pooled to resolution of the palynological record; Vinther et al., 2010), measured summer temperature anomalies from 5 meteorological stations along the Greenland coast (Büntgen et al., 2015). Shaded in light turquoise after AD 1900 indicates the period of global change impact in the Arctic. *Betula alba*-type = tree-type *Betula.*



Supplementary Table S1 Complete pollen taxa and non-pollen palynomorph (NPP) list for the palynological record of Summit Eurocore'89 (Greenland) with assignment to summary groups in the pollen diagram. Greenland taxa assignment including adventive taxa introduced since the Old Norse culture following Böcher et al. (1968) and Anderson et al. (1991). AP = arboreal pollen, NAP = non-arboreal pollen. Indication of occurrence in one ($^{+}$), two ($^{++}$) or more than two ($^{+++}$) samples of the record.

	Taxa
Native Greenland AP	*Alnus viridis*-type^{+++}, *Betula alba*-type^{+++}, *Betula nana*-type^{+++}, *Cornus suecica*-type^{++}, Ericaceae^{+}, *Juniperus*$^{+++}$, *Salix*$^{+++}$
Boreal AP	*Abies*$^{+++}$, *Calluna vulgaris*$^{+}$, *Picea*$^{+++}$, *Pinus* Diploxylon^{+++}, *Pinus* Haploxylon^{+++}, *Populus*$^{+++}$
Nemoboreal and temperate AP	*Acer rubrum*-type^{+}, *Acer saccharum*-type^{+}, *Acer* indet.$^{+++}$, *Aesculus hippocastanum*-type^{+}, *Alnus incana*-type^{+++}, *Carpinus*$^{+++}$, *Castanea*$^{+++}$, *Cornus sanguinea*-type^{+++}, *Corylus*$^{+++}$, *Fagus*$^{+++}$, *Fraxinus excelsior*-type^{+++}, *Juglans*$^{+++}$, Cf. *Liquidambar*$^{+}$, *Platanus*$^{+++}$, *Prunus*-type^{+++}, *Quercus*$^{+++}$, *Sambucus*$^{+++}$, *Taxus*$^{+}$, *Tilia*$^{+++}$, *Ulmus*$^{+++}$
Greenland NAP	*Achillea*$^{+}$, Apiaceae^{++}, *Artemisia*$^{+++}$, other Asteroideae^{+++}, *Aster*-type^{+++}, Brassicaceae^{+++}, *Campanula*-type^{++}, Caryophyllaceae^{++}, *Centaurea*$^{+}$, Cichorioideae^{++}, Chenopodiaceae^{+++}, Cyperaceae^{+++}, other Fabaceae^{+++}, *Galium*$^{+}$, Lamiaceae^{+}, Liliaceae^{+}, *Oxyria*$^{+}$, *Parnassia*$^{+}$, *Pedicularis*$^{+}$, other *Plantago*$^{+++}$, *Plantago alpina*-type^{+++}, Poaceae^{+++}, other *Polygonum*$^{+++}$, *Polygonum aviculare*-type^{+}, Primulaceae^{+}, *Anemone*-type^{+++}, other Ranunculaceae^{+}, *Ranunculus acris*-type^{++}, other Rosaceae^{+++}, *Rumex*$^{+++}$, *Sedum*$^{+}$, *Senecio*-type^{+++}, *Thalictrum*$^{+++}$, *Trifolium pratense*-type^{++}
Other NAP	*Ambrosia*$^{+++}$, *Cannabis*$^{++}$, Cerealia-type^{++}, *Helianthemum*$^{+++}$, *Herniaria*$^{+}$, *Humulus*$^{+++}$, *Hypericum*$^{++}$, *Lupinus*-type^{+}, *Plantago major*-type^{++}, *Plantago lanceolata*-type^{+++}, *Sanguisorba minor*$^{+}$, *Trollius*-type^{++}, *Urtica dioica*-type^{+++}, *Xanthium*-type^{+}, *Zea mays*$^{+}$
Fern spores	Monolete fern spore^{+++}, trilete fern spore^{++}
Fungal spores	*Ustulina*$^{+}$