1 Palynological insights into global change impacts on Arctic vegetation, fire, and

2 pollution recorded in Central Greenland ice

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21 Abstract

22 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-23 scale impacts of early- and mid-20th century industrialization and climate change on remote 24 arctic environments. Palynological analyses of Greenland ice cores may provide invaluable 25 26 insights into the long-term vegetation, fire, and pollution dynamics in the Arctic region. We 27 present the first palynological record from a Central Greenland ice core (Summit Eurocore 28 '89, 72° 35' N, 37° 38' W; the location of Greenland Ice core Project GRIP) that provides 29 novel high-resolution microfossil data on Arctic environments spanning AD 1730-1989. Our 30 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 31 Betula woodland decline during the 20th century to anthropogenic activities such as sheep 32 33 herding and wood collection in the subarctic. First signs of coal burning activities around AD 34 1900 coincide with the onset of Arctic coal mining. The use of coal and fire activity increased 35 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. 36 37 Moreover, ecosystems have changed through the spread of adventive plant species (e.g. 38 *Ranunculus acris, Rumex*) and the destruction of sparse native woodlands. We show for the 39 first time that optical palynology allows paleoecological reconstructions in extremely remote 40 sites >500 km from potential sources, if adequate methods are used.

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42 <u>Keywords</u>: <u>Betula</u> woodlands, coal mining, palaeoecology, pollen, microscopic charcoal, SCP
 43 (spheroidal carbonaceous particles)

44 **1. Introduction**

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45 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; 46 47 Vinther et al., 2010), with aerosol particles being transported to Greenland from a very wide 48 catchment area extending from the North Atlantic and the North American continent all the 49 way to the central Asian desert region (Schüpbach et al., 2018). The Greenland ice sheet 50 extends over ca. 2500 km in north-south and ca. 1000 km in west-east direction with the 51 minimum upwind distance from the Greenland summit station to the west coast being around 52 500 km. Hence, the area is extremely remote and exceptionally distant from local sources of 53 biomass and fossil fuel burning. Such a setting is ideal to investigate large-scale 54 environmental and ecological dynamics as well as the supra-regional impact of global change 55 in the Arctic by suppressing influences of local sources. 56 Palaeoecological studies from such ice cores are rare and mainly rely on molecular 57 approaches, while microfossil-based studies are lacking (De Vernal and Hillaire-Marcel, 58 2008; Willerslev et al., 2007). Existing Arctic palynological ice studies are restricted to pollen 59 source areas as well as the assessment of wind directions and generally do not fully exploit 60 the potential to reconstruct large-scale ecological and environmental dynamics (Bourgeois et 61 al., 2000; Hicks and Isaksson, 2006; McAndrews, 1984; Short and Holdsworth, 1985). On the 62 other hand, palynological studies on mire and lake deposits focus primarily on the local 63 impact on vegetation of Old Norse settlements (AD 985–1500) or formerly pristine Greenland 64 environments (Barlow et al., 1997; Bryan, 1954; Gauthier et al., 2010; Schofield and 65 Edwards, 2011; Schofield et al., 2013; Wagner et al., 2008). Consequently, little is known

67 Current observations of increased fires in thawing permafrost areas and browning of

about the large-scale impact of recent global change in these remote Arctic environments.

68 vegetation raise public concern about future environmental risks in the Arctic region (Phoenix

69 and Bjerke, 2016; Wendel, 2017). Palaeoecology may provide valuable pre-industrial base-70 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 71 72 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 73 74 reached the Arctic already since the Antiquity (Hong et al. 1994; McConnell et al., 2018) 75 while human-induced larger particle deposition may have started only with regional 76 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.

82 2. Study site and the Arctic environment

83 2.1. Climate and vegetation

Greenland has a vast glacial area of 1.8 million km² (Pfadenhauer and Klötzli, 2015) 84 and its summit (Summit station) reaches an altitude of 3232 m a.s.l. (72° 35' N, 37° 38' W). 85 86 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 87 88 amplitudes are relatively small but increase with growing continentality and in the 89 northeastern ice-free parts of the island leesides of the main ice divide, where precipitation 90 declines to 300 mm weq (Böcher et al., 1968; Mernild et al., 2015). Only a narrow ice-free 91 band along the Greenland coast hosts Arctic tundra vegetation but vast upwind areas of the 92 North American Arctic islands are covered by Arctic tundra vegetation (Fig. 1).

93 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 94 periods (temperatures below -30° C; Nentwig et al., 2004). Precipitation is not limiting for 95 96 plant growth, as evapotranspiration is low (Nentwig et al., 2004). Due to the harsh climatic 97 conditions combined with the isolated position in the North Atlantic, the modern flora in 98 Greenland itself consists only of roughly 500 vascular plants, many of which are restricted to 99 either the subarctic, low-arctic or high-arctic vegetation types (Bennike, 1999; Böcher et al., 100 1968). Subarctic vegetation is constrained to the warmest valleys in the southern and 101 southwestern part of Greenland, where summer temperatures (>8–9°C) support thickets and 102 woodlands including Betula glandulosa, Salix glauca, Alnus viridis, and the only native tree 103 species Betula pubescens, growing up to 4 m height (Böcher et al., 1968). This subarctic 104 vegetation corresponds to small patches of boreal vegetation elements within the Arctic 105 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; 106 107 Pfadenhauer and Klötzli, 2015). Finally, tall shrubs such as *B. glandulosa* and *A. viridis* are 108 absent in the high-arctic vegetation north of ca. $69-72^{\circ}$ N with mean July temperatures $<7^{\circ}$ C. 109 Instead, this vegetation type is mainly composed of *Cassiope* (Ericaceae) heathlands, bogs, 110 and grass tundra species (e.g. *Deschampsia*, *Festuca* spp., *Poa abbreviata*, *Taraxacum* 111 arcticum, T. pumilum), and Betula nana may penetrate north to 78° N (Böcher et al., 1968). 112 Although *B. pubescens* is the only native boreal tree in Greenland, few conifer species such as 113 Pinus sylvestris, P. contorta, Larix sibirica, or Picea glauca endure in small plantations in 114 southern Greenland today (Ødum, 1979). 115 The closest natural conifer forests occur in North America, where Picea mariana, P. 116 glauca, Abies balsamea, and Pinus banksiana grow up to 50° N (~2000 km southwestwards

117 from Summit; Pfadenhauer and Klötzli, 2015). American nemoboreal deciduous forests with

e.g. <u>Acer saccharum</u>, <u>Tilia americana</u>, <u>Ulmus americana</u>, and <u>Fagus grandifolia</u>, are located
about 3000 km southwest of Summit, while <u>Quercus</u> species are restricted to warmer
temperate regions further south where the latter species are also abundant (Pfadenhauer and
Klötzli, 2015).

122 2.2. Air mass transport to Central Greenland

123 The likelihood for microfossils to reach the center of the Greenland ice sheet depends 124 strongly on the atmospheric entrainment conditions at the source, the size of the source, the 125 atmospheric transport pathway, and the deposition en route. These conditions differ largely 126 for more local pollen and microscopic charcoal sources at the Greenland coast compared to 127 long-range transport of microfossils from the North American Arctic or even from Siberia. 128 A first isobaric 10-day back trajectory climatology for Summit showed that the vast 129 majority of air masses reach the Greenland summit from west and southwest (Kahl et al. 130 1997). The overall catchment area of the trajectories is centered over the northern North 131 American continent extending eastwards into the North Atlantic and westwards into Siberia 132 and Northeastern Asia. As this trajectory analysis was based on isobaric wind fields, it was 133 not able to reconstruct the three-dimensional air mass transport, which is crucial to allow for 134 the entrainment of microfossils from the boundary layer into the free troposphere and thus, for 135 long-range microfossil transport to Summit. A similar but isentropic back-trajectory cluster 136 analysis was derived for the NEEM ice core site about 650 km northnorthwest of Summit 137 (Gfeller, 2015). This analysis showed essentially the same westerly and southwesterly 138 transport of air masses to the NEEM site as observed at Summit, indicating very similar 139 general transport patterns for central and northern sites in Greenland with the highest density 140 of back-trajectories crossing the Baffin Bay and the western flank of Greenland in the free 141 troposphere for air masses within 24 hours before arrival at NEEM (Merz et al. 2014). In 142 contrast to Kahl et al. (1997), the simulations by Gfeller (2015) allowed to reconstruct the 3D

143 pathway of air masses and used this information to trace the trajectories to the point back in 144 time, when they left the boundary layer for the last time (Schüpbach et al., 2018), assuming 145 that this is the point, when the air mass was loaded with aerosol particles or larger 146 microfossils. Although the Greenland coast was masked out as potential source area, the 147 analysis shows clearly that the vast majority of air masses leaves the marine and terrestrial 148 boundary layer for the last time during summer, when the pollen load should be high, and 149 originates from the western North Atlantic and the Canadian Arctic, respectively (Schüpbach 150 et al., 2018). In particular, only very few back-trajectories stemmed from the Baffin Bay 151 region in the summer season. This air mass pattern combined with the often katabatic seaward 152 flow of air in the ice-free areas of Greenland makes a direct air mass transport from the West 153 Greenland coast relatively unlikely.

154 The microfossil load in air masses reaching Summit depends also on wet and dry 155 deposition of microfossils en route, which controls its atmospheric residence time. Thus, a 156 longer transport time and/or increased likelihood of precipitation along the transport path will 157 deplete the microfossil load during transport and generally favor more proximal source 158 regions such as the Greenland coast over distant sources such as the Canadian Arctic or the 159 mid-latitude North American continent. Due to the very long transport time from the Siberian 160 Arctic and the limited number of back-trajectories originating from this region (Gfeller, 2015; 161 Schüpbach et al., 2018), we conclude that the impact of Siberian vegetation on the Greenland 162 palynological signal should be negligible. The strong bias of air masses originating from the 163 terrestrial boundary layer of the North American continent points to a bias of the microfossil 164 origin to these regions as also supported by the occurrence of long-range transported 165 temperate Quercus, Tilia, Acer, Ulmus, and Fagus pollen in our record (see Fig. 2), which 166 cannot originate from Greenland sources. The presence of insect-pollinated *Tilia* and *Acer* is 167 particularly surprising, given that these taxa produce low amounts of pollen (Lang, 1994).

168 The longer transport time from North American sources leads to a stronger depletion of 169 the microfossil load en route compared to Greenland coastal sources. Thus, the few air masses 170 being able to reach Summit from the Greenland coast may lead to a strong palynological 171 signal despite the low number of air masses originating from the Greenland coastal boundary 172 layer and the unfavorable entrainment conditions of these sources. We conclude that our 173 palynological record from Summit in Greenland is most likely dominated by North American 174 and Greenland sources. As we are not able to distinguish between the two based on the pollen 175 signal, we interpret our record as a regional and supra-regional signal of environmental 176 change in the upwind Arctic.

177 **3. Material and Methods**

178 The ice core was drilled during the Eurocore project in 1989 at Summit in Central 179 Greenland (location of GRIP, Greenland Ice Core Project). Its chronology is based on layer 180 counting in electrical conductivity, chemical data, and acid layers of volcanic eruptions 181 (accuracy ±2 years; Blunier et al., 1993; Cachier and Pertuisot, 1994). We dedicated the 182 remaining material with a cross section of 2.5 x 2.5 cm spanning the core depth 0-80 m 183 (equivalent to the time span AD 1730–1989) to palynological analyses, with a gap between 184 58.3–61.0 m (= 11 years). Due to the isolated position of the site, the palynological analyses 185 required large ice volumes, excessive laboratory work for sample processing, and enormous 186 analytical efforts compared to mid-latitude high-alpine glacier sites (e.g. Brugger et al. 187 2018b). These site-specific properties resulted in a total of 19 samples weighing 1090–3160 g 188 (average = 2360 g) and covering ~12 years each. Microfossil extraction followed a standard 189 protocol for ice sample preparation (Brugger et al., 2018a) that allows maximum extraction of 190 rare pollen with an additional 40% HF treatment to dissolve abundant dust particles. 191 We use pollen and spores as a proxy for vegetation and land use. The counted pollen

192 sums ranged between 28 and 122 (average = 56) grains which is around the absolute 193 minimum to achieve stable percentage values for environmental reconstructions (40-50 items, 194 Heiri and Lotter, 2001). Pollen and spore identification under a light microscope at 400x 195 magnification followed Beug (2004), McAndrews et al. (1973), Moore et al. (1991), and the 196 reference collection at the Palaeoecology laboratory in Bern (Table S1). We separated Betula 197 pollen into a tree *Betula*-type (referred to as *Betula alba*-type) and a shrub *Betula*-type (*Betula* 198 nana-type; Birks, 1968; Clegg et al., 2005). We present pollen and spore data as percentages 199 of the pollen sum with summary curves (trees, shrubs) for native Greenland arboreal taxa 200 (Böcher et al., 1968; complete taxon list and assignment to summary curves in Table S1). 201 We estimated palynological richness (PRI) as a proxy for plant species richness using 202 rarefaction analysis and the probability of interspecific encounter (PIE) as a measure for 203 palynological evenness (Birks and Line, 1992; Hurlbert, 1971). We applied Principal 204 Component Analysis (PCA) to the pollen percentage data based on a correlation matrix 205 (scaling factor 2), only including native Greenland taxa, to investigate vegetation shifts in the 206 subarctic and arctic vegetation types (following Böcher et al., 1968; see Table S1). The short 207 gradient length of the first axis (= 1.57 standard deviation units) of a detrended 208 correspondence analysis (DCA, detrended by segments) justifies using linear ordination 209 methods (ter Braak and Prentice, 1988). 210 We used standard analysis for microscopic charcoal $> 10 \,\mu\text{m}$ to infer regional to supra-211 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 > 10 212 213 µm were counted to reconstruct microscopic fossil fuel pollution (Brugger et al., 2018b; Rose, 214 2015). We standardized all microfossil concentrations to one liter.

215 **4. Results and Interpretation**

216 4.1. Pollen deposition

Pollen concentrations in the Eurocore ice record are ca. 20 grains l⁻¹ in the oldest part 217 218 and increase to 50 grains 1⁻¹ after AD 1790, except in the uppermost sample with a relatively high pollen concentration (ca. 410 grains 1⁻¹; Fig. 2). This corresponds to a pollen influx along 219 the record of ca. 0.7 grains cm^{-2} year⁻¹, which increases in the top sample to ca. 7 grains cm^{-2} 220 vear⁻¹. Pollen influx in remote Central Greenland is extremely low compared to estimates 221 222 from other ice records including Arctic sites (e.g. Hicks and Isaksson, 2006). This is expected 223 because of the long distance to the closest plants. In general, the taxonomic composition of 224 the pollen assemblages is similar to that of other Arctic ice records with high portions of 225 Betula (B. alba- and B. nana-type), Poaceae, and Artemisia, which are characteristic for the 226 Arctic biome covering wide areas in the North American Arctic as well as the narrow 227 Greenland coasts. The large portions (average = 25 %) of long-distance airborne arboreal 228 pollen (AP) are remarkable, e.g. up to 10 % *Pinus* subgenus *Diploxylon* that may mainly 229 derive from the North American boreal zone, although it is also growing in temperate 230 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 231 232 trajectory analyses (Gfeller, 2015), as also documented in ice core studies from neighboring 233 North American Arctic islands (e.g. Agassiz and Devon ice caps, Bourgeois et al., 2000; 234 McAndrews, 1984). Compared to these sites with much smaller ice extent that are surrounded 235 by Arctic shrub tundra, the Eurocore at Summit contains only few pollen grains of insect-236 pollinated plants such as Ericaceae, which comprise typical plants of the Arctic shrub tundra. 237 This low amount of arctic insect-pollinated plants is likely the effect of the site isolation in 238 inland ice-covered Greenland. Pollen from plants introduced e.g. during the Old Norse 239 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 <u>Zea mays</u> grain may originate from long-distance transport (e.g.

242 North America; Thompson et al., 1999), a finding that agrees well with pollen of the

243 temperate taxa *Quercus*, *Tilia*, *Ulmus*, *Acer*, and *Fagus* in our record.

244 4.2. Vegetation dynamics

245 Two local pollen assemblage zones (LPAZ) reflect the vegetation development. LPAZ 246 Sum-1 (AD 1730–1900) consists of 50 to 60 % arboreal pollen (AP, sum of trees and shrubs), 247 suggesting the prevalence of open habitats such as arctic tundra during the period AD 1730– 248 1900 in the pollen catchment. Pollen of the only native Greenland tree (*Betula alba*-type) 249 increases to 30 % and shrub pollen (e.g. Alnus viridis type, Betula nana type, Salix, and 250 Juniperus) slightly rises to 25 % between AD 1850 and 1900, indicating a spread of subarctic 251 woodlands and thickets (Fig. 2). After AD 1900 (LPAZ Sum-2, AD 1900-1989), nonarboreal pollen (NAP, herbs) expand (e.g. Artemisia, Ambrosia, other Asteroideae, Poaceae), 252 253 while Betula alba-type, Alnus viridis-type, and Betula nana-type as well as fern spores 254 decrease, suggesting that open herb and grass tundra replaced scattered subarctic woodlands 255 and thickets. Pollen percentages of shrubs that were probably growing in the Arctic tundra 256 remain stable (e.g. Juniperus) or marginally increase (e.g. Salix). Finally, the pollen record 257 shows that Betula woodlands partly recovered around AD 1960(supported by increasing 258 influx values) and then declined to a minimum around AD 1990 (Fig. 2). 259 Pollen richness (PRI = 15-18, based on the pollen sum of 28; Fig. 2) is relatively high 260 and remains stable over the past 250 years. The pollen spectra at Summit are markedly 261 influenced by continuous and diverse long-distance pollen deposition from boreal and 262 nemoboreal tree taxa such as e.g. Quercus, Tilia, Ulmus, Acer, and Fagus deriving from 263 >2000 km distance. This long-distance pollen hampers the regional subarctic-arctic diversity 264 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).

270 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.

272 The ordination splits taxa indicative of boreal to subarctic shrub- and woodlands (e.g. *Betula*

273 <u>alba-type</u>, <u>Alnus viridis-type</u>, <u>Cornus suecica-type</u>) from arctic taxa that grow on wet (e.g.

274 Artemisia, Salix, Cyperaceae, Anemone-type) or dry soils (e.g. Poaceae, Chenopodiaceae;

275 Schofield and Edwards, 2011). Despite the clear trends with regard to taxa and sample

276 grouping, caution is needed when interpreting the ordination data as low pollen counts may

277 influence PCA results (Heiri and Lotter, 2001).

278 4.3. Fire and fossil fuel combustion

Microscopic charcoal concentration (average ca. 700 particles 1⁻¹ along the record) and 279 influx (average ca. 9 particles cm⁻² year⁻¹) are extremely low compared to other Arctic ice 280 records (ca. 200 particles cm⁻² year⁻¹ at Lomonosovfonna; Hicks and Isaksson, 2006) or to 281 Greenland sedimentary records (ca. 500 particles cm⁻² year⁻¹; Schofield and Edwards, 2011) 282 283 as a result of the large distance to the source areas. The microscopic charcoal influx suggests 284 two periods of enhanced regional fire activity around AD 1790 and after AD 1970. 285 Considering the predominant westerly wind direction (Steffen and Box, 2001), potential 286 sources include peatland fires on the Greenland coast, the North American Arctic or more 287 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

289 pollution from regional and/or long-distance fossil fuel burning (e.g. coal; Rose, 2015).

290 **5. Discussion**

291 5.1. Fire activity and fossil fuel burning in the Arctic

292 Summit recorded two major peaks in fire activity during the past 300 years, around AD 293 1790 and after 1970. The first peak correlates with increased fire activity documented at the 294 boreal forest-tundra ecotone in Alaska, possibly caused by reduced precipitation during the 295 Little Ice Age (LIA; Tinner et al., 2008) and was recorded in the black carbon (BC) record 296 from Eurocore (Cachier and Pertuisod, 1994). On the other hand, BC, ammonium, and 297 levoglucosan-based fire reconstructions from the northwestern Greenland NEEM ice core 298 suggest minimum fire activity between AD 1600 and 1750 (Legrand et al., 2016; Zennaro et 299 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 300 301 natural ignition (Calef et al., 2017; Kelly et al., 2013; Legrand et al., 2016; Soja et al., 2007; 302 Veraverbeke et al., 2017). Thus, either regional fire activity trends followed similar 303 trajectories or fire activity at Summit is reflecting distant forest fires (Thomas et al., 2017). 304 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 305 306 Isaksson, 2006). This pronounced difference is a consequence of the large distance (> 500 307 km) between the Eurocore drilling site and potential source areas. In contrast, three coal-fired 308 power stations in Svalbard are located only ca. 70 km from Lomonosovfonna glacier (Hicks 309 and Isaksson, 2006), potentially dominating its SCP record. The onset of SCP pollution at 310 Summit at ca. AD 1880 is concurrent with the start of the SCP increase in Nunatak lake in 311 Western Greenland (Rose, 2015) and in Lomonosovfonna glacier in Svalbard (Hicks and 312 Isaksson, 2006) and the rise of BC in Greenland records (McConnell et al. 2007; Fig. 4). The 313 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 314

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).

320 The increasing long-term trends of microscopic charcoal-inferred forest fire and SCP-321 inferred fossil fuel burning activity at Summit contrasts with BC and vanillic acid (VA)-based 322 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 323 324 advances, which reduced emissions to the atmosphere served as an explanation for the early 325 decline of BC (e.g. D4 record, Fig. 4; McConnell et al., 2007). In contrast to our microscopic 326 proxies, these BC records mainly capture submicron particles with a long residence time in 327 the atmosphere and thus likely reflect a continental to northern hemispheric catchment, 328 including the industrialized countries (McConnell et al., 2007). Because of the larger size of 329 microscopic particles (> $10 \mu m$), reconstructed pollution and fires may primarily come from 330 upwind American Arctic sources, as revealed by continental calibration (Adolf et al., 2018) 331 and global modelling efforts (Gilgen et al., 2018). These contrasting trends are interesting 332 because they suggest that despite declining northern hemispheric trends, microscopic-particle 333 pollution in sensitive Arctic environments probably increased as late as during the 1980s. We 334 hypothesize that in recent decades SCP may have also derived from increasing oil 335 combustion, possibly including gasoline (Rose, 2015). This is supported by reconstructed lead 336 (Pb)-pollution, which culminated in the Arctic in AD 1960–1980 and partly derived from 337 gasoline consumption (Bindler et al., 2001; McConnell et al., 2007).

338 5.2. Anthropogenic footprint on Greenland vegetation

339 The Medieval Norse culture in Greenland had a strong impact on Subarctic birch-340 willow shrublands around settlements that persisted until they were abandoned ca. AD 1350-341 1450 (Barlow et al., 1997; Berglund, 1986). The subsequent recovery of these shrub- and 342 woodlands implies a resilience of Arctic vegetation to local human disturbance similar to 343 observed vegetation recoveries after moderate anthropogenic impact of Neolithic settlements 344 in e.g. European temperate forests (e.g. Rey et al., 2017). However, our palynological record 345 from Summit suggests that the rapid colonization by alien plants (Bennike, 1999) introduced 346 by European settlers to the North American Arctic and Greenland such as Rumex or 347 Ranunculus acris was irreversible, as documented by the supra-regional pollen signal three 348 centuries later.

349 Tree Betula may form temperature-controlled tree lines (Hoch and Körner, 2003; 350 Wieser et al., 2014) in Greenland and in other Arctic areas (Anschlag et al., 2008; Hobbie and 351 Chapin III, 1998; Karlsson and Nordell, 1996). After the termination of the LIA at ca. AD 352 1850 (Fischer et al., 1998; Kaufman et al., 2009), rising temperatures increased shrub growing 353 rates in East Greenland and the Alaskan Arctic (Büntgen et al., 2015; Myers-Smith and Hik, 354 2018; Sturm et al., 2001), and allowed re-expansion of boreal forests in Alaska (Tinner et al., 355 2008) and elsewhere in the Arctic (Kullman and Öberg, 2009; Lescop-Sinclair and Payette, 356 1995; McDonald et al., 2008). In agreement, our record suggests birch woodland expansions 357 (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 358 359 further promoted expansions of Subarctic birch woodlands (Fredskild, 1991; Fig. 4). This 360 departure between temperature and vegetation dynamics coincided with the onset of Arctic 361 coal mining activities (Hicks and Isaksson, 2006; Kosack, 1967). We therefore speculate that 362 increasing human impact may have contributed to the reduction of sparse woodlands in the

Arctic during the 20th century. <u>Betula pubescens</u> woods are currently restricted to climatically 363 364 mild conditions as e.g. in Southern Greenland valleys, which are attractive for human settlements (Kosack, 1967). Although substantial portions of energy consumption were 365 366 covered by coal rather than timber burning in the Arctic, birch woodlands potentially 367 provided an additional natural resource exploitable for various purposes as e.g. for 368 constructions and fencing for cattle since natural timber sources are limited, and apart from 369 birch trees and several shrub species, wood is largely restricted to drift wood from the ocean 370 (Alix, 2005). Thus, in these northernmost ecosystems human impact during the 20th century 371 partly converted quasi-natural to anthropogenic vegetation, despite the remoteness and 372 climatically challenging natural conditions of the harsh environments (Fig. 4). Given that the 373 birch species involved is a strong pioneer, *Betula* woodlands may re-expand rapidly in the 374 future, e.g. through the establishment of woodland conservation areas (a protection area is 375 already implemented in the Qinngua valley; Austrheim et al., 2008; Ross et al., 2016).

6. Conclusions

377 Our palynological record from Central Greenland reveals that increasing anthropogenic activities at the beginning of the 20th century markedly affected Arctic environments. 378 379 Ecosystem modification included the spread of adventive plants and subarctic deforestation as 380 well as pollution from both, fossil fuel burning and increasing forest fires. Land use and 381 pollution may contribute to alter even most remote Arctic ecosystems. Specifically, pollution 382 of ice through dark microscopic particles might become of growing importance given the 383 recent increase of fire activity in Greenland (Wendel, 2017). "Blackening" of pure Greenland 384 snow and outcropping ice due to deposition of black particles may accelerate climate-385 warming feedbacks, thus reinforcing ice melting and fire risk. This study illustrates for the 386 first time that Central Greenland ice core records have a high potential for the reconstruction

387 of long-term high-resolution environmental dynamics in the Arctic. Palaeoecological ice

388 studies covering longer past periods than Eurocore '89 and reaching modern time may further

389 constrain the long-term triggers, processes, and mechanisms of rapid environmental change in

390 the Arctic.

7. Data accessibility

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

393 **8. Acknowledgments**

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399 9. References

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602 **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
- 606 island (McAndrews, 1984), 3: Baffin island (Short and Holdsworth, 1985), D4 (e.g. McConnell et al., 2007).
- 607 Sedimentary palaeoecological sites from A: Eastern Norse settlement around Igaliku lake (e.g. Schofield et al.,
- 608 2013), B: Western Norse settlement (e.g. Barlow et al., 1997), C: Nunatak lake (Rose, 2015). Subarctic
- 609 vegetation is composed of boreal vegetation elements in arctic environments, not shown in map. The map does
- 610 not display smaller ice caps in the Arctic as e.g. Devon, Baffin or Agassiz.



612 Figure 2 Pollen diagram of Summit Eurocore'89 (Greenland) shows pollen percentages of selected pollen types 613 and fern spores based on the terrestrial pollen sum with indication of taxa growing in Greenland including 614 introduced taxa by the Old Norse (adventive taxa) and taxa that are currently not growing in Greenland 615 (following Böcher et al., 1968). Portion of total Greenland native trees and shrubs from all arboreal pollen in the 616 main diagram. AP = arboreal pollen, NAP = non-arboreal pollen, t. = type. Concentration curves for pollen, 617 microscopic charcoal, and spheroidal carbonaceous particles (SCP) in particles per liter (particles 1⁻¹), influx curves for microscopic charcoal and total pollen per area per year (particles cm⁻² year⁻¹), and total terrestrial 618 619 pollen sum. Hollow curves = 10x exaggeration. Diversity estimation (Hurlbert, 1971) based on a minimum 620 pollen sum of 28 for pollen richness (PRI) and evenness index (PIE). LPAZ = visually delimited local pollen 621 assemblage zones.



Figure 3 Principal Component Analysis (PCA) for the Summit Eurocore'89 (Greenland) pollen percentage

623 624 625 626 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. <u>Betula alba</u>-type = tree-type <u>Betula</u>, <u>Betula nana</u>-t. = shrub-type <u>Betula</u>.



628 Figure 4 Comparison of Summit Eurocore '89 palynological record (pollen percentages, Betula alba-type 629 concentration and influx, microscopic charcoal influx, and SCP =spheroidal carbonaceous particles influx) with 630 independent burning and temperature records. Black carbon and vanillic acid records from the D4 site (pooled to 631 the resolution of the palynological record; McConnell et al., 2007), SCP record from Nunatak lake in Western 632 Greenland (Rose, 2015), Svalbard palynological burning records (SCP and microscopic charcoal influx; Hicks 633 and Isaksson, 2006), GRIP summer temperature (δ^{18} O in 1 year resolution and pooled to resolution of the 634 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 635 636 period of global change impact in the Arctic. <u>Betula alba</u>-type = tree-type <u>Betula</u>.



Supplementary Table S1 Complete pollen taxa and non-pollen palynomorph (NPP) list for the palynological

638 639 640 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

641 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.

642

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