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# Exotic pollen in sediments from the high Arctic Lake Tenndammen, Svalbard archipelago: diversity, sources, and transport pathways

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**ABSTRACT**

We analysed the pollen and spores extracted from 73 samples of lacustrine sediments from Colesdalen in Svalbard (Lake Tenndammen) as well as 10 soil samples collected from the lake's shores. In total, 56 pollen taxa were recorded from the sediments spanning the last 800 years, whilst 35 pollen types were found in the soil samples. Pollen was categorised as (i) regional (from Svalbard); (ii) exotic to Svalbard today; or (iii) of mixed or unclear origin. Major changes in pollen assemblages after ca 1900 CE were associated with human impact. Around 1920 CE, the first signs of introduced plant taxa were identified, by the presence of Apiaceae and Fabaceae pollen. Additionally, large-sized pollen with a thick exine and annulus diameter of 10.6–13 μm, identified as Poaceae/Cerealia type, was constantly present after ca 1920 CE. Other exotic pollen, including *Ulmus*, *Juglans*, and tropical pollen of *Albizia/Mimosa* type, *Eucalyptus* type, *Acalypha* type, and *Passiflora* type, are found only during the 1930s to 1960s, which is the period associated with the most intensive mining activity and human migration to and from Colesdalen. Furthermore, the repeated occurrence of *Myrica* (*gale*) type and *Erica* type occurring both in the lake sediment and in the soil samples is best explained by the migration of geese from Scotland (UK). Our research demonstrates how precisely human history can be reflected in the lake sediments of the Arctic environment.

## 1. Introduction

The problem of the extra-regional pollen component (also known as the long-distance component or exotic pollen) has been known since the first attempts at pollen analysis were performed (e.g. Erdtman 1920, 1921, 1937; Dokturovsky 1923; Dokturovsky and Kudryashov 1923; Cranwell and von Post 1936; Grichuk 1937; Cranwell 1938; Aario 1940; Grichuk and Zaklinskaya 1948). Pollen spectra at a given location are historically described as consisting of two main components: pollen originating from local and/or regional vegetation and pollen produced at distant sites and then transported to the location by air masses (Fægri and Iversen 1989) or other long-distance transport vectors. As Birks (1991) observed, pollen analysis of the Arctic sediments can be complicated as the concentrations of pollen and spores in the studied samples tends to be very low (e.g. Fredskild 1969; Hyvärinen 1970; Funder and Abrahamsen 1988). Furthermore, as local pollen production is low in the Arctic, the importance of the long-distance extra-regional component is increased (Surova et al. 1982; van der Knaap 1987a).

Being strongly dependent on the summer temperature, precipitation and wind, plants in the Arctic do not produce flowers annually, and not all pollen in the flowers reach maturity. These reasons often limit the application of pollen analyses in high latitudes and make the signal from regional vegetation biased. The picture is even more complicated for the pollen types known from both the regional flora and long-distance transport (e.g. pollen of *Betula*, *Salix*, Poaceae, Cyperaceae, Ranunculaceae).

To date, almost all palynological studies available from Svalbard and from adjacent isles indicate the presence of extra-regional (i.e. exotic) pollen in lacustrine sediments (Häggblom 1963; Hyvärinen 1968; Boyle et al. 2004; Dorozhkina 2005), marine sediments (Rudenko 2012, 2013a, 2013b, 2013c), peat (Blake et al. 1965; Zelikson 1971; Serebryannyy et al. 1984; Bjune et al. 2005; Rozema et al. 2006) and soil samples (van der Knaap 1987b). However, these studies do not focus on the long-distance pollen component in time or space, and little is known regarding the potential sources of exotic pollen and pollen with unknown vegetation sources. To the best of our knowledge, no specific studies have been undertaken on the extra-regional pollen component in the Arctic. In this research, we contribute to filling this gap to better understand the role of the regional, mixed and extra-regional (i.e. long-distance) pollen components in the high latitudes, which will help in the further interpretation of pollen spectra in sediments and soils of the Arctic.

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We aim to:

(i)     describe fossil pollen associations from Lake Tenndammen and compare them with modern pollen spectra described from the soil at the edge of the lake. Paying special attention to the long-distance component of both pollen spectra to discover whether there are any qualitative or quantitative differences in the pollen assemblages

(ii)    compare the reported number of pollen types and the number of exotic pollen types between our data and previously published studies, which would help in understanding whether and to what extent conditions of the local site influence pollen spectra in those places

(iii)   estimate the proportions of regional and extra-regional pollen for pollen types of regional, exotic, and unclear or mixed origin, which will shed more light on the problem of pollen sources and pollen origin

(iv)    to estimate the minimum pollen count required for the comprehensive description of palynoflora in Svalbard (and potentially other high-latitude study sites), and the effect this has on estimates of richness. This knowledge is crucial in designing palynological and palaeoecological studies, but often disregarded when the concentration of pollen seems low at first glance – which is typical for Arctic, marine and glacial sediments. However, this problem can be overcome by additional efforts applied in filtering and concentrating pollen if its diversity appears to be relatively low and if the minimal count approach suggests feasible numbers.

## 2. History of palaeoecological research in Svalbard

According to Ingólfsson and Landvik (2013), the best overviews of the Late Pleistocene to Holocene palaeogeographical changes in Svalbard (Spitsbergen, Шпицберген) are reflected in the following lithostratigraphical profiles: Kongsøya (Ingólfsson et al. 1995); Kapp Ekholm (Mangerud and Svendsen 1992); 'Miller's profile' N15 (Miller et al. 1989); Lennéelva (Lønne and Mangerud 1991); Skilvika (Landvik et al. 1992); Poolepynten (Andersson et al. 1999); Kongsfjordhallet (Houmark-Nielsen and Funder 1999); Murchisonfjorden and Nordaustlandet (Kaakinen et al. 2009) (see Table 1 and Figure 1A). A detailed palaeogeographical study of environmental changes from the Late Dryas to the Subatlantic period in Svalbard (Spitsbergen), that involved almost all data available at that time, was presented by Surova et al. (1982). The next comprehensive summary of the late glacial environmental changes in Spitsbergen was given by Birks et al. (1994).

The first pollen analysis in Svalbard was probably performed by Środon (1960) (Table 1) from the 60 cm deep peat profile from Hornsund at Isbjørnhamna, near the Polish Polar Station. He studied the long-distance pollen and spore transport and provided two radiocarbon dates (1266–1441 cal AD and 540–820 AD) with 95.4% probability according to Blake et al. (1965; in the original, 620 ± 80 and 1390 ± 70 years uncal. BP), obtained at the University of Uppsala, Sweden. His findings were similar to those of Kuprianova (1951), who did research in other regions of the High Arctic, i.e. in Franz-Josef Land, Severnaya and Novaya Zemlya.

The first pollen analyses of lake sediments were presented by Häggblom (1963) and later by Hyvärinen (1968), who analysed pollen and diatoms in the profiles from the Bjørnøya Island. He also reconstructed the history of Lake Trulvatnet in Nordauslandet, based on the pollen-analytical studies (Hyvärinen 1969). Altogether, Hyvärinen analysed five lake sediment profiles from the Bjørnøya Island and Nordaustlandet, which represented the last 10,000 years of regional history (Hyvärinen 1970). He also focused on the problematic pollen types and reconstructions of climatic changes (Hyvärinen 1972), the results of which were discussed by Tobolski (1975). The studies of Häggblom in Nordaustlandet (Häggblom 1963), Blake et al. (1965) in Hornsund, and Hyvärinen (1968, 1970) on the Bear Island (Bjørnøya) revealed that by about 11,000 BP the regional flora was 'similar to the present one' (Bernardova and Košnar 2012). Zelikson (1971) also performed pollen analysis of peats from the Semmeldalen supported by radiocarbon dating (116 cal. BC–380 cal. AD to 379 cal. BC–202 cal. AD with 95.4% probability; in the original: 1910 ± 110 to 2070 ± 110 years uncal. BP) and found that conditions for peat accumulation in Svalbard were favourable throughout the Holocene. The same was indicated by Surova et al. (1982), who studied mid-Holocene peats from Adventdalen and early Holocene peats from Reindalen and interpreted the previously published data from the Semmeldalen.

Later palaeoecological studies of the Holocene sediments in Svalbard were carried out by van der Knaap (1985, 1986, 1987a, 1987b, 1988a, 1988b, 1988c, 1989, 1990, 1991) and Rozema et al. (2006). van der Knaap (1988c, 1989) suggested that the vegetation of Svalbard was moderately rich in species before ca 4000 BP, an observation also made by Birks (1991). Surova et al. (1982, 1986) undertook pollen analysis of the Svalbard region, analysing a 250 cm deep profile from Colesdalen (Surova et al. 1988). The location of their studies was relatively close to ours (thus they utilised peat core material and lake sediments). These authors indicated dominance of those pollen types that have mixed and/or unclear origin in terms of their source vegetation, e.g. *Betula*, Cyperaceae, Poaceae –types that make up a significant part of the airborne and sediment pollen spectra in the high latitudes.

A few peat deposits from Spitsbergen have been studied for pollen, spores and macrofossils (Blake et al. 1965; Zelikson 1971; Serebryannyy et al. 1984; van der Knaap 1985, 1988c). Dynamics of the past vegetation cover and climatic conditions were reconstructed from the end of the late ice age to the sub-Atlantic period by Serebryannyy et al. (1984, 1993). In 2007, Dorozhkina published the results of her pollen analyses of the sediments from Fuglechuken cape. The 295 cm deep profile she analysed spanned the Atlantic to Sub-boreal (3259–2898 cal. BC, 3622–3361 cal. BC, 4450–4251 cal. BC; in the original: ca 5500 ± 50 uncal. BP, 4670 ± 45 uncal. BP, 4370 ± 40 uncal. BP). The last available comprehensive study of the past vegetation in Svalbard was performed by Jankovská (1994, 1995, 2017).

## 3. Study area

### 3.1. Study site: Tenndammen and its catchment

Tenndammen (Figure 1) is small shallow lake located in Colesdalen, Nordenskiöld Land, western Svalbard. The lake

**Table 1.** Geographical position, altitude and vegetation palaeo-proxies studied in some sediment profiles of Svalbard.

| Site code | Name | Latitude (N) | Longitude (E) | Altitude (m) | Vegetation palaeo-proxies studied | References |
|---|---|---|---|---|---|---|
| 1 | Hakluythovden | 79°46′27″ | 10°45′10″ | 10.0 | ☉ | Birks et al. 2004 |
| 2 | Salatberget | 79°45′53″ | 10°43′00″ | 10.0 | ☉ | Birks et al. 2004 |
| 3 | Kobberfjorden | 79°41′00″ | 10°54′00″ | 50.0 | (☉) | Birks et al. 2004 |
| 4 | 'Kobberfjorden Pond' | 79°41′00″ | 10°48′42″ | 10.0 | (☉) | Birks et al. 2004 |
| 5 | 'Draba Pond' | 79°48′20″ | 11°33′20″ | 20.0 | (☉) | Birks et al. 2004 |
| 6 | 'Bjørnvatnet' | 79°40′10″ | 10°48′30″ | 70.0 | ☉ NPP | Birks et al. 2004 |
| 8 | Sverrefjellet Volcano* | 79°25′ | 13°25′ | 507 | ☉ | Berglund and Ralska-Jasiewiczowa 1986 |
| 10 | Signedalen | 79°15′57″ | 11°32′30″ | 30.0 | ☉ | Birks et al. 2004 |
| 11 | Hajeren | 79°15′30″ | 11°33′30″ | 35.0 | ☉ | Birks et al. 2004 |
| 12 | Trongdalen | 79°11′37″ | 11°39′25″ | 45.0 | (☉) | Birks et al. 2004 |
| 13 | 'Ossian North' | 78°57′25″ | 12°30′20″ | 50.0 | (☉) | Birks et al. 2004 |
| 14 | Ossian Sarsfjellet | 78°57′04″ | 12°28′38″ | 60.0 | ☉ | Birks et al. 2004 |
| 15 | McVitiepynten | 78°52′25″ | 10°54′40″ | 20.0 | (☉) | Birks et al. 2004 |
| 16 | 'Murraybreen Pond' | 78°45′13″ | 11°06′06″ | 30.0 | (☉) | Birks et al. 2004 |
| 17 | Hamnetangen | 78°19′26″ | 12°50′47″ | 20.0 | ☉ | Birks et al. 2004 |
| 18 | Veslekulpen | 78°15′57″ | 12°55′26″ | 20.0 | ☉ | Birks et al. 2004 |
| 19 | Ytertjørna | 78°13′52″ | 12°56′30″ | 20.0 | ☉ | Birks et al. 2004 |
| 20 | Spålen | 78°13′12″ | 13°20′40″ | 20.0 | (☉) | Birks et al. 2004 |
| 21 | Tenndammen | 78°06′00″ | 15°02′00″ | 5.0 | ☉ | Birks et al. 2004 |
| 22 | Colesdalen** | 78°05′12″ | 15°08′00″ | 20–50 | ☉ NPP ❀ sedaDNA | Serebryannyy et al. 1984, 1993; Surova et al. 1988; Edwards et al. 2018; Poliakova et al. (in prep.). |
| 23 | Isfjorden, 3 marine cores** | 78°20′ | 15°00′ | sea | ☉ | Rudenko 2012, 2013a, 2013b, 2013c |
| 22, 24 | Vassauga | 77°45′30″ | 13°57′20″ | 15.0 | ☉ | Birks et al. 2004 |
| 23, 25 | Daltjørna | 77°33′50″ | 14°13′55″ | 55.0 | (☉) | Birks et al. 2004 |
| 24, 26 | Skardtjørna | 78°00′ | 13°40′ | 65 | ☉ ❀ | Birks 1991 |
| 25, 27 | Linnévatnet | 78°2′42″ | 13°48′36″ | ca 87** | ☉ ❀ | Svendsen et al. 1987, 1989; Mangerud and Svendsen 1990; Birks 1991 |
| 26, 28 | Adventelva catchment** | 78°10′48″ | 16°1′12″ | 14–15 | ❀ | Holyoak 1984 |
| 27, 29 | Brøggerhalvøya** | 78°55′ | 12°00′ | 30 | ☉ ❀ | van der Knaap 1985; 1988c |
| 28, 30 | Rosenbergdalen** | 78°4′30″ | 20°55′ | 50 | ☉ ❀ | van der Knaap 1989 |
| 9 | Stuphallet** | 79° | 15° | 30 | ☉ | Hyvärinen 1970; Rozema et al. 2006 |
| 7 | Søre Salatberget | 79°70′ | 11° | 40 | ☉ | Hyvärinen 1970 |
| 29, 31 | Hornsund area** | 76°57′43″ | 15°34′23″ | Up to 260 | ☉ | Środon 1960; Blake et al. 1965 |
| 30, 32 | Raddedalen | 78°1′22″ | 21°39′21″ | 68–78 | ☉ | Bjune et al. 2005 |
| 31, (S7), 33 | Trullvatnet, Murchisonfjorden, Nordaustlandet | 74°32′ | 19°31′ | 1 | ☉ | Hyvärinen 1969; 1970; Birks 1991 |
| 32, (S16),34 | Søre Russøya, Murchisonfjorden, Nordaust landet | 79°58′ | 18°15′ | 38** | ☉ | Häggblom 1963, as indicated on the map (fig. 1) in Bernardova and Košnar 2012, Hyvärinen 1970; Birks 1991 |
| 33, (S28),35 | Strøen, Wijdefjorden, Dirksbukta, Vestspitsbergen | 74°32′ | 19°30′ | 14** | ☉ | Hyvärinen 1970; Birks 1991 |
| 34, 36 | Ny Ålesund** | 78°55′0″ | 11°56′0″ | 18 | ☉ | Johansen and Hafsten 1988; Rozema et al. 2006 |
| 35, 37 | Isdammen** | 78°12′36″ | 15°44′37″ | 3.3 | ☉ | Rozema et al. 2006 |
| 36, 38 | | 77°58′00″ | 15°23′48″ | 76 | ☉ | Zelikson 1971 |

**Table 1.** Continued.

| Site code | Name | Latitude (N) | Longitude (E) | Altitude (m) | Vegetation palaeo-proxies studied | References |
|---|---|---|---|---|---|---|
| | Semmeldalen, 9 km north of Van Mijenfjorden** | | | | | |
| 39 | Grøndalen close to Barensburg** | 77°59′8″ | 14°38′48″ | 75 | 🌀 | Serebryannyy et al. 1984, 1993 |
| 37, 40 | Core POL_I 'Scottehytta' | 78°42′11″ | 16°36′54″ | 4 | Θ | Bernardova and Košnar 2012 |
| 38, 41 | Core Cassio | 78°43′4″ | 16°26′20″ | 24 | Θ 🌀 | Bernardova and Košnar 2012 |
| 39, 42 | Fuglekhuken cape, Prince Carl Land | 78°89′ | 10°47′ | 8–80 | Θ | Dorozhkina 2007 |
| 43 | Nurdamen Lake, Bünsow Land, Western Spitsbergen | 78°32′10″ | 16°59′55″ | No data ca 900 | Θ | Dorozhkina 2005 |
| 44 | Lake Skartjørna | 77°57′42″ | 13°49′10″ | 61 | 🌀 sedaDNA | Alsos et al. 2016 |
| 45 | Lake 'Jodavannet' Ringhorndalen | 79°20′18″ | 16°1′8″ | 140 | sedaDNA | Voldstad 2018 |
| 46 | Endalen** | 78°10′39″ | 15°41′39″ | 50 | 🌀 soil eDNA | Edwards et al. 2018 |

Notes: Θ – pollen data; (Θ) – pollen was found in the samples, but there was not enough material for analysis (according to Birks et al. 2004). 🌀 – Plant macrofossil data; NPP – Data on non-pollen palynomorphs; DNA – data on sedaDNA. * – Open terrain peats at the foot of Sverrefjelet Volcano in the NW part of Svalbard, Bockfjorden region (Berglund and Ralska-Jasiewiczowa 1986). ** – not given by the author(s) of the original paper, instead retrieved from the modern map (Norwegian Polar Institute, https://toposvalbard.npolar.no) and/or using the literature. Lake code refers to the map in Figure 1A and indicates the lake position. eDNA – environmental DNA.
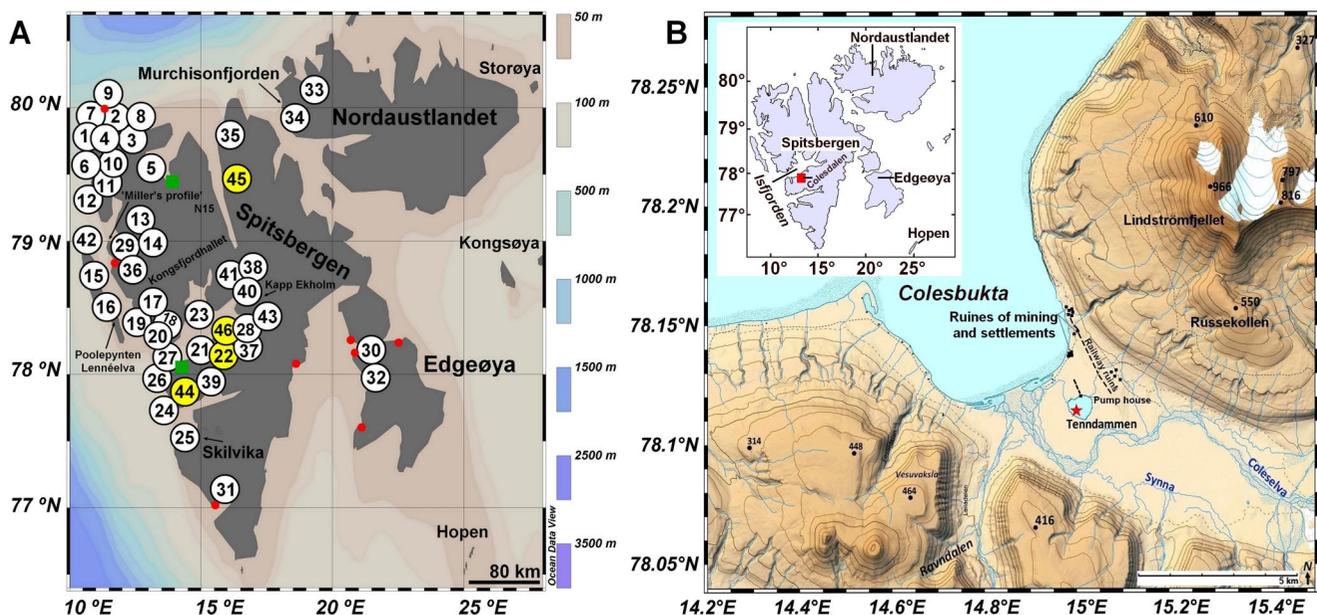


**Figure 1.** (A) Palaeogeographical and palaeoecological studies in the Svalbard archipelago. White circles with numbers indicate sampling sites (see Table 1). Yellow circles show ancient and environment DNA studies; green squares refer to the research cases, in which the studies were performed but the results were not officially published (available in the form of expedition reports and/or internal institutional documents); red circles indicate palaeoecological studies mentioned in literature but the original publication was not found. (B) Research area, position of Lake Tenndammen and a coring site. Created with the free available software QGIS 2.18.15 (http://qgis.org.), data derived from the open source: Interactive map of Svalbard (Norwegian Polar Institute, https://toposvalbard.npolar.no).

catchment has a complicated geomorphological and hydrological history that is described in detail by Poliakova et al. (in prep.).

The lake's modern catchment is approximately one-tenth the maximum size of the historical catchment (2.5 km² vs. 20.5 ± 0.2 km², measured according to https://toposvalbard.npolar.no) although it is occasionally increased by flood-flows from the main Colesdalen River. At present, only one stream flowing towards Isfjorden drains the lake at its western side. Two smaller water streams flow from the Russekollen highlands (413–550 m asl; Figure 1B) and discharge into the lake

at its north-eastern edge. In the middle of the twentieth century the lake and its catchment experienced extensive human activity involving coal mining from 1911 to 1913, until the operation was closed in 1962 (https://arcticugol.ru); water was uptaken by pumping from the lake and supplied to the Colesbay and Grumant miners' settlements (Figure 2) before their closure in 1988 (https://arcticugol.ru).

Various forms of evidence of activities associated with coal mining and transportation, power production and water pumping are still found on the coasts of Tenndammen as well as near the sea shore, including coal mine remains, the

building of a coal-burning power plant (Figure 2A), a coal shipping pier and associated infrastructure (Figure 2B), an old water pump house, other piping debris, abandoned houses, and railway tracks (Figure 2C and D).

Coal mining and related human activities in Colesbukta began in the early years of the twentieth century (1909–1916), followed by the construction of the Colesbukta and Grumant settlements, with a coal port and a power plant, in 1911–1913. The peak of coal mining occurred in the 1950–1980s, driven by the high demand for electricity due to the development of Svalbard (https://arcticugol.ru; Rose et al. 2004).

### 3.2. Regional climate, winds and marine currents

Svalbard is characterised today by a cold arid Arctic climate (Köppen-Geiger type EF/ET, Beck et al. 2018), although it is less extreme in the south and central areas than the more northern and eastern parts, because the North Atlantic Ocean Current brings warm water along the west coast of the archipelago. The mean annual air temperature at Svalbard Airport is −3.9 °C. The mean air temperatures of July and February are +7.0 and −11.6 °C, respectively, although Colesdalen has higher summer temperatures (Lang et al. 2007), and as a consequence is one of the sites in Svalbard that supports the highest diversity and concentration of thermophilic species (Engelskjøn et al. 2003, Alsos et al. 2004; Arnesen et al. 2014). Precipitation is frequent but relatively low, typically less than 400 mm year$^{-1}$ in western Spitsbergen, but up to 1000 mm year$^{-1}$ on the uninhabited east side (Torkildsen 1984; Hanssen-Bauer et al. 1990).

Wind in Svalbard is common and is relatively strong (Figure 3). In summer, calm days are more common than strong winds, but a low pressure may always move through, bringing 1–2 days of strong wind or even storm. The risk of strong winds increases in autumn and winter; it is at its lowest in June and July. Cold polar air from the north and wet sea air from the south meet and mix over Svalbard. Therefore, low pressure and changeable weather with high wind speeds occur in the archipelago, especially in winter. A



**Figure 2.** (A) Remains of the coal-burning power station in the former settlement Grumant (1912–1965). In the background is a narrow-gauge railway running from the coal mine to the port of Colesbukta. (B) Buildings of the miner's settlement Colesbukta with two warehouses, two piers, several leaving houses, a canteen and a coal processing plant. At the seashore a coal port can be seen. (C) General view from the Russekollen highland on the Colesdalen with the river Coleselva and its tributary Synna flowing into Lake Tenndammen and Colelbukta of the Isfjord. (D) View of Lake Tenndammen from its shore. Remains of wooden and metal constructions can be seen. In the left corner – former water piping station. **Photos A-B:** taken and provided by Dr. Dmitry Prochorov; **C:** derived from the open source: https://en.wikipedia.org/wiki/Colesdalen, **D:** taken by Prof. Inger Alsos.

**Wind directions and wind frequency distribution**
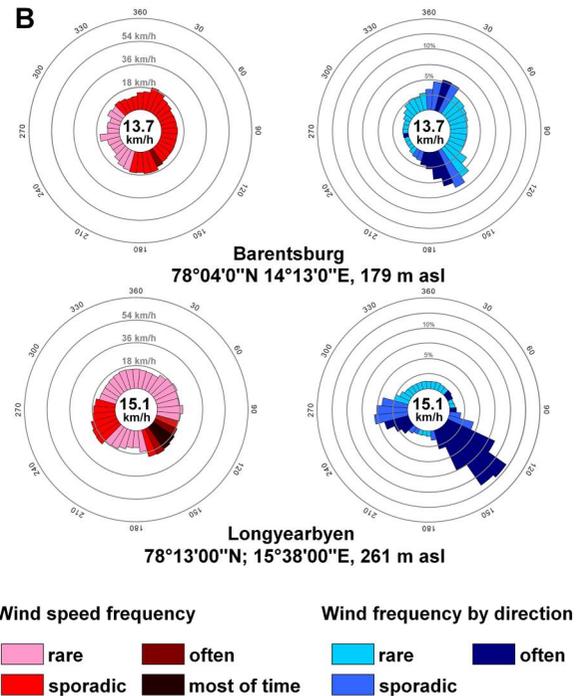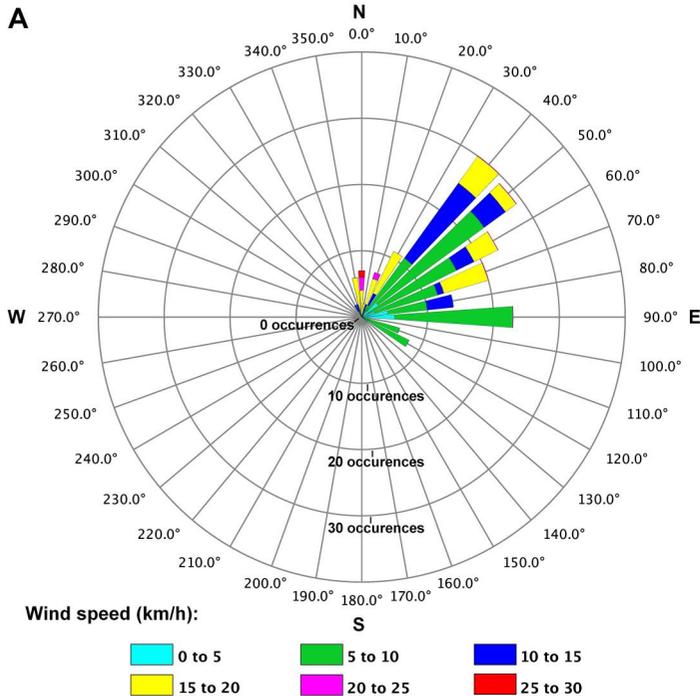
Russekollen: 78.12°N; 15.17°E, 413 m asl



**Figure 3.** (A) Local wind rose for the Russekollen highland (about 4 km from study site). (B) Diagrams for wind speed frequencies (left side, red) and for prevailing wind directions (right side, blue) at weather stations in Barentsburg (19 km from study site) and Longyearbyen (20 km from study site). Data are retrieved from the open source: https://www.meteoblue.com/en/.

strong breeze is registered ca 17% of the time at Isfjord Radio in January, and only ca 1% of the time in July. As Figure 3A demonstrates, most winds in Colesdalen and surrounding areas come from the north-east, with the strongest gusts coming from north. Open sites receive winds from either direction, but south-east (the strongest) and north-east (the most frequent) winds prevail (Figure 3B, Barentsburg). Elevated and mountain-surrounded places receive predominantly strong and often south-east winds (Figure 3B, Longyearbyen). Colesdalen combines characteristics of both described sites and fog is common (Torkildsen 1984; Hanssen-Bauer et al. 1990). The general pattern of supra-regional wind directions is shown in Figure 4 (black arrows).

The weather and climate conditions on Spitsbergen are largely affected by the oceanic waters surrounding the island: the Greenland Sea in the west, the Barents Sea in the east, the Norwegian Sea in the south, and the Arctic Ocean in the north. A warm West Spitsbergen Current (WSC, Figure 4), with average water temperature of 5–7 °C, runs along the western coast of Spitsbergen (Walczowski and Piechura 2006).

On the east side of the island, however, some of the ice-cold waters of the East Spitsbergen Current (ESC) flow round the south end of Spitsbergen and head north as the so-called Sørkapp Current (Figure 4). Warm Atlantic waters coming with the WSC are particularly important in shaping the island's climatic conditions. In recent years the temperature and salinity of the waters have risen significantly. This affects weather and climate conditions both globally and locally, especially on the west coast of Spitsbergen

(Walczowski and Piechura 2006, 2011; Piechura and Walczowski 2009; Styszyńska 2011). The system of oceanic currents and the heat exchange between the ocean and the atmosphere influence the range and concentration of sea ice. At the time of its maximum extent (i.e. in March/April), sea ice envelops the whole of Spitsbergen. Towards the end of summer, however, there is a substantial difference between the west and the east coasts of the Svalbard archipelago. In the west, the sea is often free from sea ice as far as northernmost Spitsbergen, whereas in the east, sea ice flows from the north and, having passed the Sørkapp, is driven far along the west coast of Spitsbergen in a northward direction (Haugan 1999; Walczowski and Piechura 2006).

The WSC is of importance because it drives warm and salty Atlantic Water into the interior Arctic (Haugan 1999). The warm and salty WSC flows north through the eastern side of Fram Strait, while the East Greenland Current (EGC, Figure 4) flows south through the western side of Fram Strait. The EGC is characterised by being very cold and low in salinity, but above all else it is a major exporter of Arctic sea ice. Thus, the EGC combined with the warm WSC makes the Fram Strait the northernmost ocean area having ice-free conditions throughout the year in the entire global ocean (Haugan 1999).

### 3.3. Modern vegetation

A general description of the vegetation peculiarities in Colesdalen is presented in Poliakova et al. (in prep.).
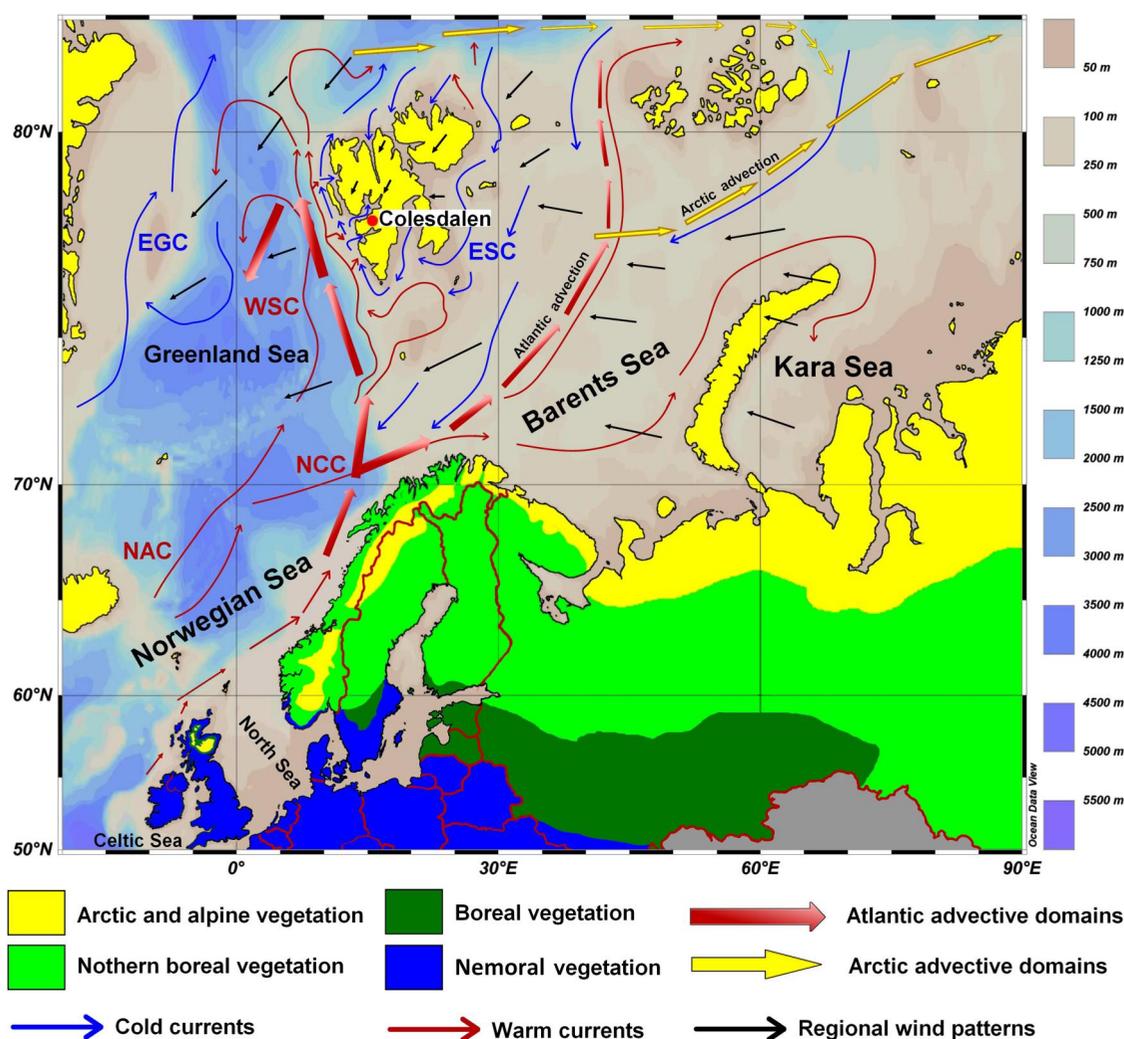
**Figure 4.** Distribution of main types of northern-European vegetation (i.e. arctic and alpine, northern boreal, boreal, and nemoral) as potential pollen sources, with regional patterns of winds and marine currents in the northern Atlantic and the western part of the Arctic Ocean. Warm currents are abbreviated as follows: NAC – North Atlantic Current, NCC – North Cape Current, WSC – West Spitsbergen Current. Cold currents are indicated as EGC – East Greenland Current, ESC – East Spitsbergen Current. The upper layer advective domain of the European sector of the Arctic Ocean and the Atlantic (wide red arrow) and Arctic (wide yellow arrow) Data on vegetation derived from the Plants of the World Online website (https://www.powo.science.kew.org). Advective domains are depicted following Wassmann et al. (2019).

Tenndammen is surrounded by mires with abundant *Eriophorum scheuchzeri* around the northern and western shores. *Salix polaris*, *Carex*, *Juncus* and Poaceae species create most of the vegetation cover of the Colesdalen valley. Bryophytes, including submerged species (e.g. *Calliergon*, *Drepanocladus*, and *Scorpidium*), are very common. Vegetation on surrounding slopes is characterised by the presence of various *Draba* species, *Bistorta vivipara*, *Dryas octopetala*, *Saxifraga* and Poaceae species (Elvebakk and Prestrud 1996; Elven and Elvebakk 1996; Elvebakk 1997). Bare ground comprises about 20–30% of the study area within 4–10 m of the lake (Birks et al. 2004; Poliakova et al. in prep).

*Salix polaris*, *Stellaria longipes*, *Festuca rubra* ssp. *arctica* and *Trisetum spicatum* are common at most sites in Colesdalen (Alsos and Lund 1999). *Poa* and *Ranunculus* species can occupy snow beds (Elvebakk 1994) and high Arctic polar desert/stony tundra and zonal vegetation is characterised by *Draba* species, *Papaver dahlianum*, *Pedicularis hirsuta*, *Saxifraga cernua*, *S. cespitosa* and *S. oppositifolia*, with participation of *Phippsia* and *Cerastium* (Daniëls et al. 2016).

The south-facing slope of the Colesdalen and the west-facing slope at Rusanovodden host a number of species that are rare in Svalbard. Two of these, i.e. *Campanula rotundifolia* ssp. *giesekiana* and *Juncus squarrosus*, have not been detected elsewhere on the archipelago (Alsos 2004). Furthermore, five plants found in Colesdalen (*Euphrasia wettsteinii* G. Gussarova, *Campanula rotundifolia* L. ssp. *giesecki-ana* (Vest) Mela and Cajander, *Vaccinium uliginosum* L. ssp. *microphyllum* Lange, *Rubus chamaemorus* L. and *Betula nana* L. ssp. *tundrarum* (Perfil.) Á. Löve and D. Löve) have their northernmost worldwide boundaries in Svalbard (Alsos et al. 2002, 2004; Engelskjøn et al. 2003; Eidesen et al. 2007; Arnesen et al. 2014; Poliakova et al. in prep.).

## 4. Material and methods

### 4.1. Sediment and soil samples

Sediment core Te2019 (85 cm long and 6 cm in diameter) was collected from the central part of Lake Tenndammen (78°06.118′N, 15°02.024′E, 5 m asl; Figure 1B) with a modified

Nesje sediment sampler (Nesje 1992). The core was sampled for pollen and other proxies (Poliakova et al. in prep.) at a resolution of 2 cm throughout except the topmost 30 cm, where sampling was carried out every 0.5 cm. In total, 73 samples (Figures 5 and 6) from the same depths were taken for all proxy analyses; to avoid potential destruction of pollen and spores, no vortexing was applied.

Additionally, 10 thin soil samples (Table 2; Figure 7; Supplementary material: Figure S1) were randomly taken from the upper soil horizon on the shores of Lake Tenndammen at distances between 1 and 4 m from the water body. Coordinates and details of the soil samples are given in Table 2. Samples were processed as described in section 4.3.

## 4.2. Pollen analysis

Pollen and spore analysis was performed on 5 g of sediment material according to the standard methods (Faegri and Iversen 1989; Poliakova et al. in prep.). In the case of soil, all collected material was used as the pollen content in the samples was very low. Sediment samples were processed at the Department of Palynology and Climate Dynamics of the Göttingen University. Soil samples were processed at the Arctic University Museum of Norway, Tromsø. One tablet of *Lycopodium clavatum* (number of spores 20,848 ± 1546, batch numbers 1031 and 113, series 78) was added to each sample at the first step of chemical treatment to enable estimation of the pollen concentration (Stockmarr 1971). Samples were sieved through 150 μm mesh; due to the very low initial pollen concentration both in sediment and in soil samples, each residue was sieved over a 10 μm nylon filter to remove smaller fractions and to concentrate pollen material. No hydrofluoric acid (HF) treatment was applied to the soil samples. Samples were mounted in glycerine gelatine and examined under a light microscope at magnifications of × 400, × 600 and × 1000. A minimum of 100 pollen grains were
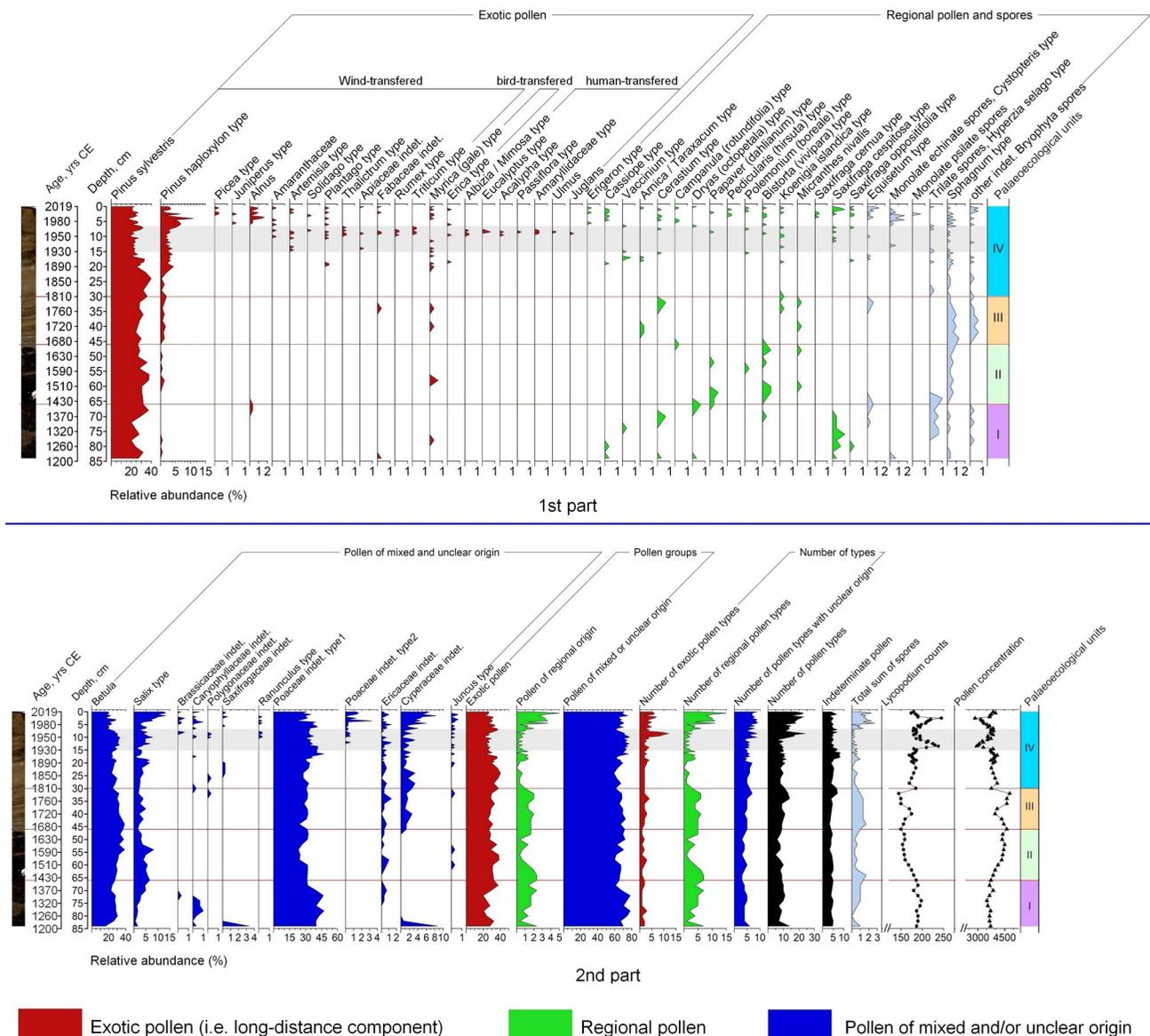


**Figure 5.** Pollen stratigram showing relative abundances of the individual pollen types; sums of exotic pollen, regional pollen and pollen of mixed or unclear origin; numbers of exotic pollen types, regional pollen types and pollen of mixed or unclear origin; general numbers of pollen types, *Lycopodium* marker counts and pollen concentrations. The period between 1930 and 1966 in the stratigram is marked in grey. Palaeoecological units are applied as in our further study (Poliakova et al. in prep.).
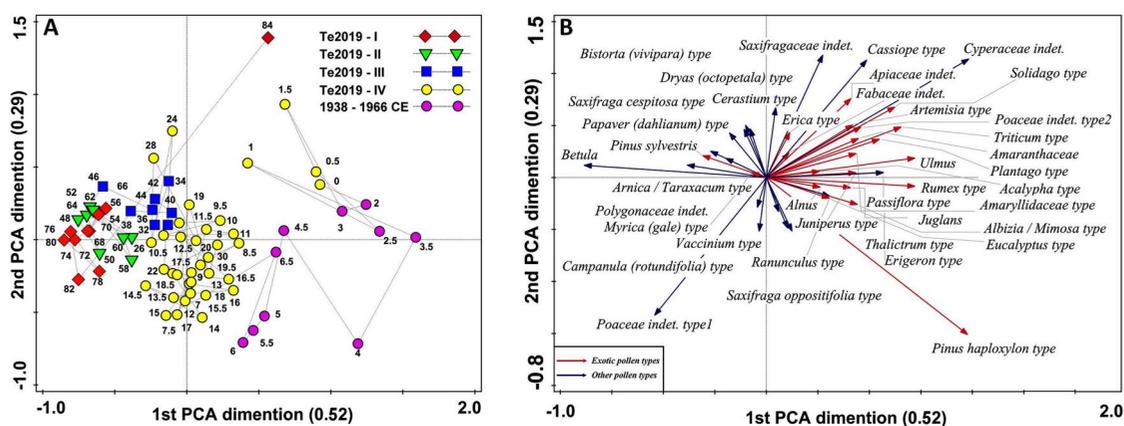
**Figure 6.** Results of principal component analysis (PCA) illustrating statistical relations of selected pollen types and sediment samples collected from the indicated core depths. The relative distance between samples explains the differences in pollen cyst composition. (A) Clusters of sediment samples clearly reflect pollen zones TePol-1 to TePol-4 indicated in Figure 6. (B) Only dominant pollen types with abundance greater than 5% and exotic types are included.

**Table 2.** Position of the soil probes collected from the lake shores and sample volumes.

| Sample name | Longitude (N) | Latitude (E) | Wet/dry mass of the sample (g) |
|---|---|---|---|
| Te001 | 78°06.111′ | 15°01.895′ | 20.356/18.156 |
| Te002 | 78°06.081′ | 15°01.364′ | 25.654/20.364 |
| Te003 | 78°06.004′ | 15°00.991′ | 23.565/20.665 |
| Te004 | 78°05.952′ | 15°01.025′ | 26.115/18.165 |
| Te005 | 78°05.933′ | 15°01.370′ | 25.126/23.357 |
| Te006 | 78°05.859′ | 15°01.819′ | 25.165/23.369 |
| Te007 | 78°05.856′ | 15°02.370′ | 25.169/24.155 |
| Te008 | 78°05.944′ | 15°02.660′ | 25.168/19.688 |
| Te009 | 78°06.048′ | 15°02.708′ | 25.388/23.198 |
| Te010 | 78°06.097′ | 15°02.481′ | 26.168/20.136 |

counted for the soil samples and 300 pollen grains for sediment samples. To reach the required count, several slides were prepared per sample.

Pollen identification was performed at the Department of Palynology and Climate Dynamics, University of Göttingen, and partly at The Arctic University Museum of Norway using modern and fossil pollen reference collections and pollen keys (Moore et al. 1991; Reille 1992; Faegri and Iversen 1994; Bennett 2004; Beug 2004; Yao et al. 2012, 2014). All identified pollen and spore types were photographed with a digital camera. Pollen not identified to below the family level is marked 'indet.' (e.g. Caryophyllaceae indet.). In cases where identification is uncertain but pollen morphology suggests a certain pollen type, the word 'type' is used together with a pollen name (e.g. *Plantago* type). If the morphology suggests two identification possibilities, both taxa are indicated (e.g. *Arnica/Taraxacum* type). For some pollen, the species was not identified morphologically but is floristically suggested as only one species of the genus in question is known to occur in the research area and/or the presence of other species of the genus is highly unlikely. This is indicated by enclosing the species name in parentheses (e.g. *Campanula* (*rotundifolia*) type). If more than one morphological type was described to the same level of taxonomical resolution, types 1 and 2 are mentioned (e.g. Poaceae indet. type 1 and Poaceae indet. type 2). To compare selected pollen variables individually, pollen concentrations (grains $cm^{-3}$) were estimated throughout the sediment sequence. Although some palynologists routinely distinguish pollen of *Betula nana*

from other *Betula* types (e.g. Zelikson 1971; Surova et al. 1982, 1988; Troitskiy et al. 1985; Dorozhkina 2005, 2007; Rudenko 2012) the preservation conditions of our material did not allow reliable differentiation of *Betula nana* under the light microscope, so we refer to pollen of *Betula* sensu lato. Plant taxonomy follows the Angiosperm Phylogeny Group (2016). The subfamily Chenopodioideae is included in the family Amaranthaceae.

## 4.3. Pollen diagrams

Pollen diagrams were prepared using TILIA/TILIA.GRAPH software (Grimm 2004). Local zones on the stratigram for the sediment core Te2019 were established visually by comparing the fluctuations of the principal taxa and groups, supported by the results of the depth-constrained cluster analysis by sum of squares implemented with CONISS for TILIA (Grimm 1987). The stability of the classification and the sharpness of the clusters (probability: $1 \leq p > 0$) were tested using the bootstrap resampling performed in MULTIV (Pillar and Orlóci 1996; Pillar 1999). All pollen types were attributed to groups that correspond to most-probable pollen origin. Three groups of pollen and spores were established (see Figure 5; Supplementary material: Table S1 and Figure S1):

1. Pollen of regional origin. This includes pollen and spores of the plants that are known from local flora of the Colesdalen valley or from the whole of Svalbard (following Elvebakk 1994, 1997; Elvebakk and Prestrud 1996; Elven and Elvebakk 1996; Svalbardflora.no).
2. Exotic pollen. This comprises pollen of plants that do not grow in Svalbard today and, as far as we know, did not grow there in the past, i.e. arboreal pollen (*Pinus*, *Picea* type, *Juniperus* type, *Alnus*, *Corylus*, *Ulmus*, *Juglans*), pollen of Amaranthaceae, Asteraceae (excluding *Taraxacum*, *Petasites* and *Arnica*), *Myrica* (*gale*) type, *Erica* type, *Plantago* type, *Thalictrum* type, and *Triticum* type. This group also includes pollen from tropical plants (i.e. pollen of *Albizia/Mimosa* type, *Eucalyptus* type, *Acalypha* type, *Passiflora* type, *Amaryllidaceae* type) and pollen of synanthropic plants, only known after 1950 from
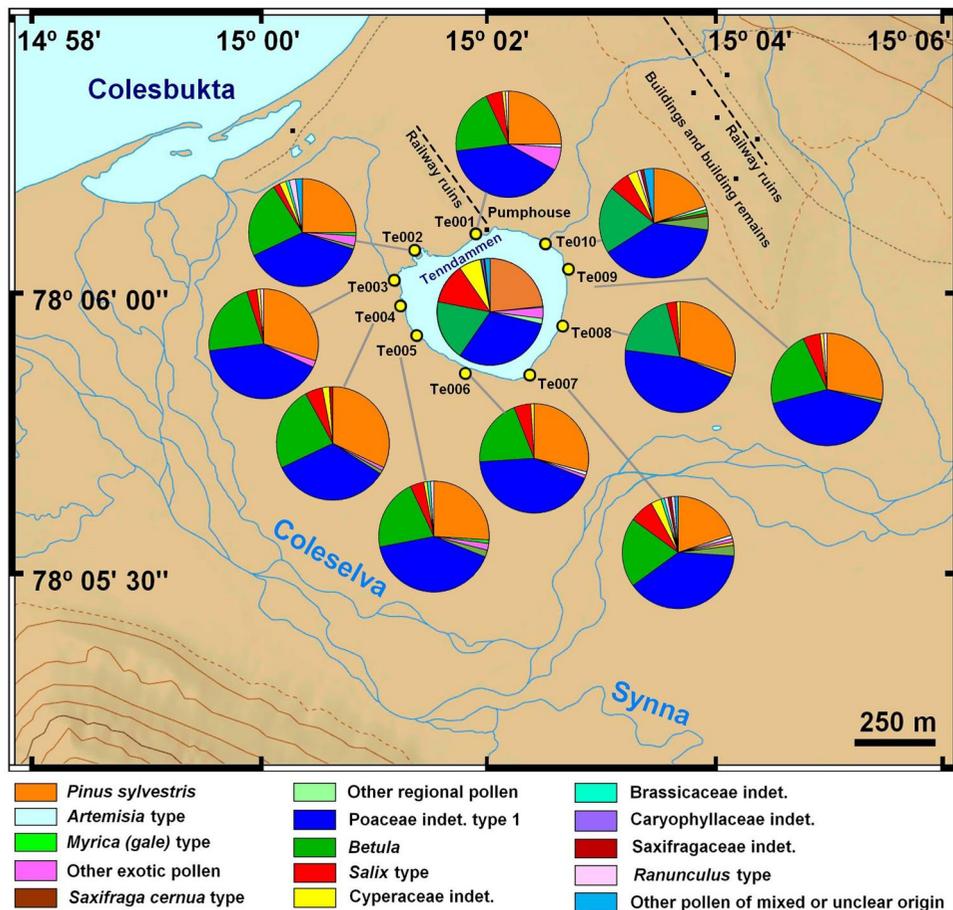
**Figure 7.** Pollen relative abundance charts showing spectra for 10 soil samples collected around Lake Tenndammen in 2019. At the surface of the lake a pollen diagram for the uppermost sediment layer (0 cm) is presented. Coordinates of the soil probes are given in Table 2. Map is created based on the openly available Interactive map of Svalbard (Norwegian Polar Institute, https://toposvalbard.npolar.no).

settlements in Svalbard, i.e. pollen of Apiaceae indet., Fabaceae indet., and *Rumex* type (Svalbardflora.no).

3. Pollen of mixed or unclear origin. This group includes pollen types whose origin is difficult to determine. Potential source plants are known from Svalbard, and pollen of these plants is also known from the long-distance component of other Arctic regions as these plants produce large amounts of pollen that travel en masse via winds and marine currents: e.g. *Betula*, *Salix* type, Brassicaceae indet., Caryophyllaceae indet., Polygonaceae indet., Saxifragaceae indet., Ranunculus type, Poaceae indet., Ericaceae indet., Cyperaceae indet. and *Juncus* type. The exotic pollen were not included in the cluster analysis used to establish local pollen zones. In further data analysis all pollen groups were included. An age–depth model for the Te2019 sediment core was used as we describe it in Poliakova et al. (in prep.).

Pollen diagrams compare pollen and spore spectra from the sediment core Te2019 (Figure 5) and from soil samples (Figure 7). Diagrams present relative abundances of individual pollen types, that were calculated on the basis of the total pollen sum excluding indeterminate pollen. Group sums as well as numbers of pollen/spore types identified within each group accompany the percentage profiles. Furthermore, pollen concentrations (pollen per gramme of dry sediment) are given as well as group ratios (Figure 5). A full pollen diagram for the soil samples can be found in the Supplementary material (Figure S1).

## 4.4. Multivariate data analysis

Multivariate data analysis was carried out on pollen percentage data using the programmes Canoco for Windows 4.5 and CanoDraw for Windows 4.13 (ter Braak and Šmilauer 2002). All pollen taxa that were present in at least two samples, in at least one of which a value of >1% was reached, were included in the analysis. This criterion was chosen to decrease the effect of rare taxa that do not explain the overall vegetation trend well. First, a detrended correspondence analysis (DCA, Hill and Gauch 1980) was conducted to determine the length of the environmental gradient, which had a value of only 1.5. Thus, a linear model could better explain data and reflect it in a more comprehensive way. We therefore performed a principal component analysis (PCA). For both analyses, all taxonomical data were standardised and logarithmically transformed. This removes the bias from very dominant taxa and improves the fit of the count data. In order to evaluate the significance of the PCA axes, the null hypothesis was tested using the nonparametric Monte Carlo permutation test (Manly 1992). Under the null hypothesis it is expected that no relations exist between the variation in

pollen relative abundance and sample depths. Comparison of the present and the previous pollen studies are performed with the Sørensen index of similarity (Sørensen 1948; Carass et al. 2020).

## 5. Results

### 5.1. Sediment samples

In total, 51 pollen and six spore types were distinguished, with 23 exotic types (12 arboreal and 10 herbal pollen types with addition of *Passiflora* being herbal or woody vine), 22 pollen and spore types of regional origin and 12 pollen types of mixed or unclear origin (see Figure 5 and Supplementary material: Table S1 for details). As the pollen content was as low as 10–50 grains per slide, additional concentration through the 10 μm nylon filter was applied. The average pollen concentration throughout the entire core was only ca 3812 ± 407 pollen grains per mL of sediment. A comparison of the type–count curves (cf. Brown 1999) shows the accumulation curve for the overall sample has the expected steep shape, levelling off at approximately 80 grains counted, which indicates a local to regional supply of common types. In contrast, the exotic curve has a lower and shallower gradient that levels off only after a count of 220 or more, due to the relative rarity of these long-distance types. Thus, the types are drawn from two different populations. Although most of the regional pollen diversity is likely encountered in 80 grains, their actual proportions might not be properly captured until a count of 250 grains is reached. Therefore, higher counts per slide are recommended to produce a more statistically robust representation of the pollen proportions, which is important for interpreting the past vegetation, especially if the research aims to also reflect the long-distance component of the regional pollen spectra.

In our study the 15 most dominant pollen types are those found within the count of the first ca 15 grains (Supplementary material: Figure S2). A linear increase of diversity is observed within the count of the first ca 43 grains, reaching 27 types; the diversity increase proceeds until the count reaches 88 (47 pollen and spore types), while at a count of 300 grains, only nine additional rare pollen types occur (Supplementary material: Figure S2). This supports the contention that the exotic group has a different source to the regional group.

The pollen assemblages are mainly composed of pollen of mixed and/or unclear origins: Poaceae indet. type 1 (ca 34 ± 5.6%), *Betula* (ca 27 ± 5%) and exotic pollen of *Pinus sylvestris* (ca 27 ± 4%). Those pollen types were found in all 73 samples, together with the *Salix* type that does not account for more than ca 5 ± 3%. The *Pinus haploxylon* type is found in 59 samples, Cyperaceae indet. is registered in 56 samples, and Ericaceae indet. is known from 50 samples. The most common spore type was *Sphagnum* (in 43 sediment samples). In only one sample were the exotic *Eucalyptus* type (Plate 1, figure 1), *Passiflora* type (Plate 1, figure 2) and *Ulmus* (Plate 1, figure 3) registered (all registered as single grains at a depth of 8.5 cm from the top of

the core 1956 CE), as well *Juglans* (at 9 cm 1954 CE; Plate 1, figure 4) and monolete psilate spores (two spores occurred at 2.5 cm, 1987 CE). Other pollen and spore types are found in 2–18 samples. The taxonomical composition of pollen associations supported by cluster analyses allows us to describe four distinct stratigraphical zones (TePol-1 to TePol-4; Figures 5 and 6).

Pollen zones TePol-1 to TePol-4 (Figure 6) are clearly depicted in the PCA ordination: clusters of samples reflect the CONISS stratification, implying additionally a sub-cluster with samples from 6 to 2 cm within the zone TePol-4; those dated to the period from 1938 CE to 1966 CE, respectively. The first two dimensions of the PCA (Figure 6) account for 52% and 29% of the total variance of data, respectively. The null hypothesis that no relations exist between the variation in pollen relative abundance and sample depth was rejected at $p = .05$.

The ratio $\lambda 1 + \lambda 2$/total variance, a measure of the goodness of fit equivalent to $R^2$ (Jongman et al. 1987), is 0.86. The sample taken from 84 cm core depth is set apart from all other groups of samples (Figure 6A) as it contains a relatively large amount (9%) of Cyperaceae pollen (Figure 6B) in comparison to all other samples, whichmakes it an outlier. Proportions of the main pollen groups remain relatively stable along the core: regional pollen contributes 1–2% (Figure 5), long-distance extra-regional pollen forms about 29%, and pollen with mixed and/or unclear origin dominates pollen spectra in Colesdalen at 70% (Figure 5). These proportions vary within two standard deviation (SD) among pollen zones Te2019-I–Te2019-IV.

Correlation between samples within the same cluster is relatively strong, mean $R^2$ (at $p < 0.001$) varies from 0.62 (Te2019-IV) to 0.83 (Te2019-III). Samples from the depths 1 to 0 cm are characterized by presence of pollen of *Artemisia* type, *Alnus*, *Plantago* type, *Thalictrum* type, Apiaceae indet., Fabaceae indet. as well as crop plant pollen, i.e. Poaceae indet. type 2 (large-sized pollen grain with a thick cell wall) and Triticum type (Figures 5, Figure 6B). Pollen of the crop plants makes rather small contribution to the total pollen sum (not more that 5–7% all together), so the allocation of these samples into a separate subcluster is statistically unsupportable with only a 0.30 level of probability (sensu Pillar & Orlóci 1996; Pillar 1999), despite this being suggested by ordination of samples.

### 5.1.1. Zone Te2019-I (66–84 cm; 10 samples; 1202–1396 years CE)

The exotic pollen (~27%, five pollen types; Figure 5) in this zone mainly consists of *Pinus sylvestris* (about 26%). Other types make minimal contributions: *Pinus haploxylon* type, *Alnus*, Fabaceae indet. (Plate 1, figure 5), and *Myrica* (*gale*) type (Plate 1, figure 6). Pollen of regional origin (ca 2% of total pollen sum; Figure 5) comprises by eight pollen types and five spore types, none > 1%. Pollen of mixed or unclear origin (about 71%; Figure 5) includes eight types, with the greatest contribution from Poaceae indet. type 1 (~40%), *Betula* (~25%) and *Salix* type (~3%; Figure 5).
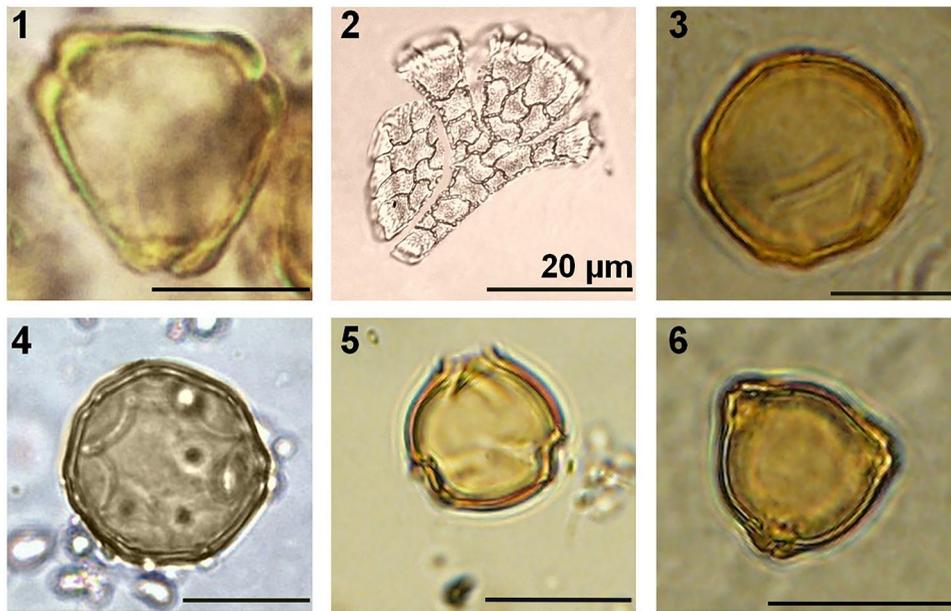
**Plate 1.** Light microscope pollen photographs (magnification × 400) of selected exotic taxa found in sediment core Te2019: 1. *Eucalyptus* type; 2. *Passiflora* type; 3. *Ulmus*; 4. *Juglans*; 5. Fabaceae indet.; 6. *Myrica* (*gale*) type; Scale bars: 1 and 3–6 = 10 µm; 2 = 20 µm.

### 5.1.2. Zone Te2019-II (48–64 cm; 9 samples; 1418–1668 years CE)

The exotic pollen component is formed by three types, with *Pinus sylvestris* at ~32% (Figure 5) and the other two types, i.e. *Pinus haploxylon* type and *Myrica* (*gale*) type (Plate 1, figure 6), contributing less than 1% combined. Pollen of regional origin (1% of total pollen sum; Figure 5) shows reduced numbers in terms of both pollen and spores (four and three, respectively), none > 1%. Pollen of mixed or unclear origin (~67%; Figure 5) adds five types, with *Betula* contributing ~32%, Poaceae indet. type 1 decreasing to ~28% and *Salix* type increasing to ~5% (Figure 5).

### 5.1.3. Zone Te2019-III (32–46 cm; 8 samples; 1685–1807 years CE)

Exotic pollen contributes ca 29% (4 types, Figure 5), with pollen of *Pinus sylvestris* decreasing to ~28%. Other types are *Pinus haploxylon* type, Fabaceae indet. and *Myrica* (gale) type (Plate 1, figure 6). Pollen of regional origin (2% of total pollen sum; Figure 5) is represented by six pollen types and three types of spores; none forms > 1%. Pollen of mixed or unclear origin (69%; Figure 5) includes seven types. The most abundant are *Betula* (~34%), Poaceae indet. type 1 (slightly increasing in this zone, ~30%), *Salix* type (reducing to ~3%) and Cyperaceae indet. adding ~2% (Figure 5). Other three types, i.e. Juncus, Ericaceae indet. and Polygonaceae indet. contribute only single grains.

### 5.1.4. Zone Te2019-IV (0–30 cm; 46 samples; 1825–2019 years CE)

All 23 exotic pollen types are registered in this zone (Figure 5), including seven types that occur only in this zone: *Picea* type, *Juniperus* type (Plate 2, figure 1), Amaranthaceae indet. (Plate 4, figure 1), *Artemisia* type (Plate 2, figure 3), *Solidago* type (Plate 2, figure 4), *Plantago* type (Plate 2, figure 5), and

Apiaceae indet. (Plate 2, figure 6). In addition, 11 types occurred exclusively in samples from 8 to 9.5 cm: *Rumex* type (Plate 3, figure 1), *Triticum* type (Plate 3, figure 2), *Thalictrum* type (Plate 3, figure 3), *Albizia/Mimosa* type (Plate 3, figure 4), *Eucalyptus* type (Plate 1, figure 1), *Erica* type (Plate 3, figure 5), *Acalypha* type (Plate 3, figure 6), *Passiflora* type (Plate 1, figure 2), *Amaryllidaceae indet.* type (Plate 2, figure 2), Ulmus (Plate 1, figure 3) and *Juglans* (Plate 1, figure 4). Rare regional pollen types of e.g. *Campanula* (*rotundifolia*) type (Plate 4, figure 4), *Arnica/Taraxacum* type (Plate 4, figure 5), and *Polemonium* (*boreale*) type (Plate 4, figure 6) are also registered mainly in this zone. Exotic pollen forms 30% (Figure 5), with *Pinus sylvestris* (26%) and *Pinus haploxylon* type (3%) being the strongest contributors. Pollen of regional origin has the highest number of types (15 types of pollen and six types of spores), but they account for only 1% of the total pollen sum. *Erigeron* type, *Pedicularis* (*hirsuta*) type, *Saxifraga cernua* type, and monolete spores psilate spores are only found in this zone (Figure 5). Pollen of mixed or unclear origin accounts for 69% of the total and comprises 21 pollen and spore types. Mainly to the total pollen sum in this zone contribute Poaceae indet. type 1 – 34%, *Betula* – 25%, *Salix* type – 5% and Cyperaceae indet. – 2%. Two pollen types, i.e. *Ranunculus* type and Poaceae indet. type 2, are registered only in this zone (Figure 5).

### 5.2. Pollen spectra of soil samples

In total, 31 pollen types and four spore types were distinguished in the soil samples, with 17 exotic types (eight arboreal and nine herbal pollen types), four pollen and four spore types of regional origin, and 11 types of mixed or unclear origin (see for details Figure 5 and Supplementary material: Table S1). Pollen content was low (about 40–70 pollen grains per slide); this increased to 110 grains per slide after filtering through the 10 µm nylon filter. Pollen

**Plate 2.** Light microscope pollen photographs (magnification × 400) of selected exotic taxa found in sediment core Te2019: 1. *Juniperus* type; 2. Amaryllidaceae indet. type; 3. *Artemisia* type; 4. *Solidago* type; 5. *Plantago* type; 6. Apiaceae indet. Scale bars: 10 μm.



**Plate 3.** Light microscope pollen photographs (magnification × 400) of selected exotic taxa found in sediment core Te2019: 1. *Rumex* type; 2. *Triticum* type; 3. *Thalictrum* type; 4. *Albizia/Mimosa* type; 5. *Erica* type; 6. *Acalypha* type. Scale bars: 1–3 and 6 = 10 μm; 4 = 40 μm; 5 = 20 μm.

concentration was as low as ca 3137 ± 1366 pollen grains per mL of sediment and ranged from 1930 (Te003) to 5346 (Te010) and 5791 pollen grains per mL of sediment (Te007).

The taxonomical diversity of the soil samples was about 10.8 ± 3.8 types. The composition of the pollen assemblages is generally similar to that of the sediment samples: pollen with mixed and or unclear origin contributes the most, about 69.6 ± 2.8% (from 66% in Te004 to 74% in Te007). Exotic pollen adds about 28.9 ± 3.8% on average, ranging from 22% (Te007 and Te010) to 33% (NN 1 and 4). Regional pollen contributes about 1.5 ± 1.6% (up to 4% in Te007 and 5% in Te010). In samples Te001, Te003 and Te006, no pollen of regional origin was encountered.

Poaceae indet. type 1 contributes ca 40.3 ± 3%, ranging from 34% (Te004) to 46% (Te009); *Pinus sylvestris* contributes ca 26.5 ± 4%, ranging from 20% (Te010) to 32% (Te004 and Te009); *Betula* contributes ca 21 ± 1.5%, ranging from 19% (Te009) to 43% (Te006). The *Salix* type stays at about 4.5 ± 1.4%, ranging from 2% (Te002) to 7% (Te007). These taxa occur in each of the 10 soil probes. Pollen of *Quercus/Fagus* type (Plate 4, figure 2) and *Carpinus* type (Plate 4, figure 3) were found in only one sample (Te001; Figure 7).

### 5.3. Multivariate analysis

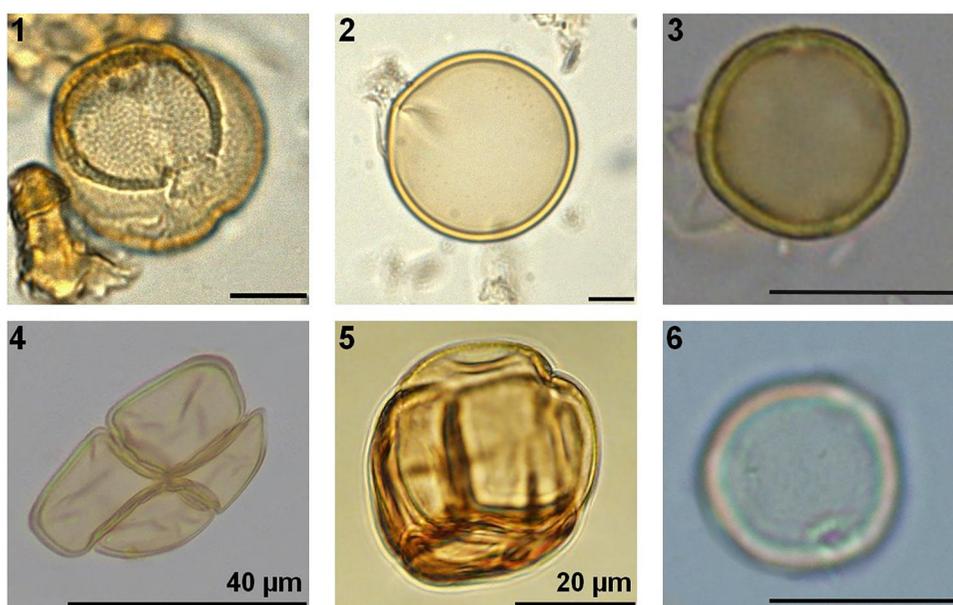A comparison of the pollen taxonomical diversity in the soil samples with the pollen diversity of the Te2019
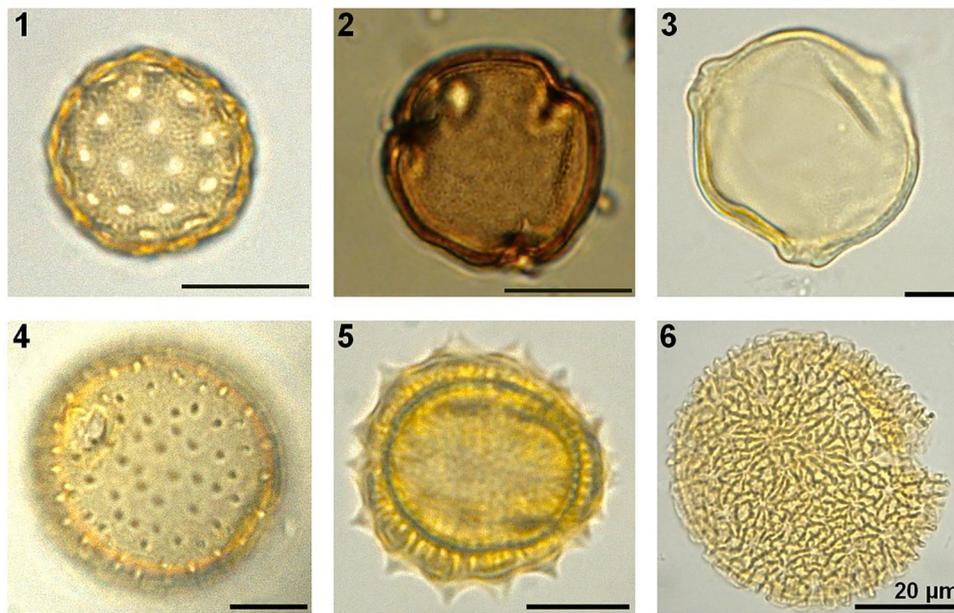
**Plate 4.** Light microscope pollen photographs (magnification × 400) of selected exotic taxa found in sediment core Te2019: 1. Amaranthaceae indet.; 2. *Quercus/Fagus* type; 3. *Carpinus* type; 4. *Campanula* (*rotundifolia*) type; 5. *Arnica/Taraxacum* type; 6. *Polemonium* (*boreale*) type. Scale bars: 1–5 = 10 μm; 6 = 20 μm.

**Table 3.** Comparison matrix of pollen taxonomical diversity in the soil probes collected on the shores of Tenndammen Lake (A); pollen zones of the sediment core Te2019: Te2019-I (B), Te2019-II (C), Te2019-III (D), Te2019-IV (E), the whole of Te2019 (F); previous studies in Svalbard conducted in different years: Hyvärinen 1970 (G), Surova et al. 1982 (H), van der Knapp 1988a (I), Birks et al. 2004 (J), Dorozhkina 2007 (K), Jankovská 2017 (L), and all previous studies F–L together (M). Bold figures in blue cells on the diagonal are the number of diagnosed pollen types; grey cells below the diagonal show the number of taxa shared between the two compared studies; white cells above the diagonal show the Sørensen index of similarity for the two compared studies.

|   | A | B | C | D | E | F | G | H | I | J | K | L | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A | **35** | 0.78 | 0.52 | 0.31 | 0.52 | 0.1 | 1 | 0.4 | 0.35 | 0.39 | 0.16 | 0.43 | 0.48 |
| B | 32 | **27** | 0.67 | 0.79 | 0.1 | 0.78 | 0.66 | 0.29 | 0.53 | 0.63 | 0.35 | 0.28 | 1 |
| C | 13 | 18 | **57** | 0.27 | 0.15 | 0.9 | 0.8 | 0.38 | 0.09 | 0.64 | 0.22 | 0.29 | 0.24 |
| D | 10 | 14 | 11 | **40** | 0.57 | 0.95 | 0.52 | 0.37 | 0.58 | 0.33 | 0.43 | 0.1 | 0.31 |
| E | 18 | 26 | 14 | 12 | **22** | 0.94 | 0.33 | 0.95 | 0.86 | 0.71 | 0.81 | 0.3 | 0.2 |
| F | 32 | 56 | 19 | 15 | 26 | **39** | 0.89 | 0.31 | 0.67 | 0.93 | 0.67 | 0.3 | 0.95 |
| G | 21 | 22 | 10 | 7 | 12 | 22 | **29** | 0.15 | 1 | 0.94 | 0.8 | 0.31 | 0.47 |
| H | 19 | 20 | 9 | 8 | 13 | 20 | 18 | **24** | 0.47 | 0.06 | 0.56 | 1 | 0.03 |
| I | 18 | 21 | 9 | 10 | 14 | 22 | 16 | 13 | **32** | 0.12 | 0.36 | 0.27 | 0.89 |
| J | 21 | 24 | 11 | 8 | 15 | 25 | 16 | 13 | 19 | **40** | 0.9 | 0.42 | 0.63 |
| K | 17 | 20 | 10 | 8 | 13 | 20 | 14 | 15 | 11 | 12 | **22** | 0.13 | 1 |
| L | 17 | 26 | 13 | 10 | 19 | 27 | 18 | 16 | 18 | 20 | 17 | **39** | 0.94 |
| M | 13 | 38 | 16 | 13 | 22 | 39 | 29 | 24 | 31 | 38 | 22 | 17 | **71** |

stratigraphical zones (Table 3) and other studies shows that the greatest similarity is between the lake surface samples (studies A and B), between the peat samples (J and K) and between the soil samples and peat samples (between studies A and G; between studies G and I). (See the Table 3 caption for an explanation of these study group letters.) Studies from the same site or similar conditions (G and I; H and L) show the highest similarity in terms of pollen taxonomical diversity as well (see Supplementary material: Table S1 and Figure S3).

## 6. Interpretation and discussion

In general, the pollen assemblages in sediment core Te2019 and in the lake shore soil samples shows high similarity in terms of both taxonomical composition and percentages of the most common pollen types, these being Poaceae indet. type 1, *Pinus sylvestris* and *Betula*, with some contribution of *Salix* type and Cypecaceae. Variation in the pollen proportion is slight (never higher than 2SD); this corresponds with the results of previous studies and is well discussed in the literature for Svalbard/Spitsbergen (Środon 1960; Hyvärinen 1970; Surova et al. 1982, 1988; Serebryannyy et al. 1985; van der Knaap 1985, 1988a, 1988b, 1989; Birks et al. 2004; Dorozhkina 2007; Jankovská 2017) (Table 4) and for Bjørnøya as well as for Nordaustlandet (Hyvärinen 1970). In terms of pollen origin, mixed sources of pollen predominate in our study as well as in the previously published ones.

Considering the technical differences in the equipment available to researchers at different times and taking into account progress in the study of the pollen morphology, a test on the influence of the publication date was performed (see Supplementary material: Figure S4). It revealed that the quality of the pollen record is not influenced by the year of publication; furthermore, the taxonomical richness, of all pollen and spore types and of exotic pollen specifically, is not highly influenced by the nature of the samples analysed (e.g. peat vs. lake

**Table 4.** Overview of pollen analysis cases in Svalbard with regard to the total sum of counted pollen grains per slide (Scount), pollen concentration (C, grains cm$^{-3}$) and/or pollen influx (Inf, cm$^{-2}$ year$^{-1}$) if given, total number of registered exotic pollen types (Nexotic) and their relative abundance (% exotic).

| NN | Site code | Name | C, grains cm$^{-3}$ and/or Inf, cm$^{-2}$ year$^{-1}$ | Scount | Ntotal | Nexotic | % exotic | References |
|---|---|---|---|---|---|---|---|---|
| 1 | 1 | Hakluythovden | <1000* | At least 150 (up to 225) land pollen and spores* | 45 | 12* | 27 | Birks et al. 2004 |
| 2 | 2 | Salatberget | | | | | | |
| 3 | 6 | 'Bjørnvatnet' | | | | | | |
| 4 | 10 | Signedalen | | | | | | |
| 5 | 11 | Hajeren | | | | | | |
| 6 | 14 | Ossian Sarsfjellet | | | | | | |
| 7 | 17 | Hamnetangen | | | | | | |
| 8 | 18 | Veslekulpen | | | | | | |
| 9 | 19 | Ytertjørna | | | | | | |
| 10 | 22, 24 | Vassauga | | | | | | |
| 11 | 21 | Tenndammen | | | | | | |
| 12 | 21 | Tenndammen | 3600–4400 after concentration of material | At least 100 (up to 300) terrestrial pollen types excluding LDC | 57 | 15 | 26 | Poliakova et al. in prep., and this paper |
| 13 | 22 | Colesdalen | Not indicated | 100–200? | 42 | 5 | 12 | Serebryannyy et al. 1984, 1993; Surova et al. 1988 |
| 14 | 8 | Sverrefjelet Volcano | Not indicated | 100–200? | 40 | At least 7** (!) | 18 | Berglund and Ralska-Jasiewiczowa 1986 |
| 15 | | Advendsdalen | Not indicated | 100–400 per slide | 21 | 4 | 19 | Surova et al. 1982 |
| 16 | | Rainsdalen | | | 22 | 5 | 23 | |
| 17 | 23 | Isfjorden | Not indicated | 150–200 terrestrial grains | At least 15** | Not indicated | NA | Rudenko 2012 |
| 18 | 24, 26 | Skardtjørna | <1000 | Not indicated | Not indicated | Not indicated | NA | Birks 1991 |
| 19 | 25, 27 | Linnevatnet | <1000 | All | 23 | 5** | 22 | Svendsen et al. 1987, 1989; Mangerud and Svendsen 1990; Birks 1991 |
| 20 | 27, 29 | Brøggerhalvøya, bird cliff | Exotic pollen influx: 3.4 grains | 100–200? | 32 | 13 | 41 | van der Knaap 1988a |
| 21 | 28, 30 | Rosenbergdalen | | | 23 | 5 | 22 | |
| 22 | 9 | Skinkevatna | <1000 | 40(50) – 100* | 28 | 10 | 36 | Hyvärinen 1970 |
| 23 | 7 | Ellasjøen | | | 29 | 10 | 34 | |
| 24 | 31, 33 | Trullvatnet | | | 23 | 7 | 30 | |
| 25 | 33 | Støre Russøya | | | 18 | 7 | 39 | |
| 26 | 35 | Strøen | | | 25 | 8 | 32 | |
| 27 | 30, 32 | Raddedalen. Peat samples | ~1000 or less | 247–604 | 21 | 10** | 48 | Bjune et al. 2005 |
| 28 | 35, 37 | Ny Ålesund peat core | Not indicated | 141–480 | 21** | 8** | 38 | Rozema et al. 2006 |
| 29 | | Blomstrand peat core | | 0–331 | 17** | At least 4** | 24 | |
| 30 | | Stuphalllet peat core | | 0–653 | 15 | At least 4** | 27 | |
| 31 | | Isdammen peat core | | 228–356 | 32 | At least 7** | 22 | |
| 32 | 37, 40 | Core POL_I 'Scottehytta' | Max 30 | All | Not indicated | Not indicated | NA | Bernardova and Košnar 2012 |
| 33 | 39, 42 | Fuglehuken cape, Prince Carl Land | Not indicated | 56–336 | At least 12** | At least 5** | 42 | Dorozhkina 2007 |

Note:
*– This number is given for all studied lakes together (Birks et al. 2004).
**– Not indicated by the authors, derived from text and/or diagram.
? – The pollen count per slide is not indicated by the authors but is suggested by the method applied.
! – The *Betula alba* indicated in the original diagram cannot in fact be identified under the light microscope at the level of species due to morphological restrictions, so this pollen type was regarded here and further as *Betula* pollen without a species assignment.
For a comparison matrix of these records with each other and with our sediment and soil studies, see the Supplementary material (Figure S3).

sediments). Nevertheless, the record obtained under the bird cliff (van der Knaap 1988a) does not match the trend of general diversity or exotic pollen diversity (Supplementary material: Figure S4).

## 6.1. Exotic pollen in palynological spectra of the Svalbard Archipelago

The long-distance extra-regional pollen component forms about 29% both in our sediment samples and in the soil samples (Figures 5–7), and this well coincides with the average percentage (29.1 ± 9.1%) of exotic pollen calculated based on the previous palynological studies in Svalbard (Table 4), with a variation of 12% according to the earlier studies in Colesdalen (Serebryannyy et al. 1984, 1993; Surova et al. 1988) (Table 1; Figure 1A) and of 48% in peat samples from Raddedalen (Bjune et al. 2005) (Table 1; Figure 1A). The earliest works show a high contrast to these findings: up to 80% extra-regional pollen was calculated to occur Holocene lake sediments from northern Svalbard (Hyvärinen 1970) and from Bjørnøya (Hyvärinen 1968). In contrast, later pollen spectra obtained for from Reindalen and Adventdalen (Surova et al. 1982) indicate that the long-distance extra-regional component there forms from 1% to 51% (ca 30% on average) in those peat samples and was created mainly by Pinus and Alnus with some participation of herbs (Artemisia, Asteraceae). Surova et al. (1982) found that the contribution of the long-distance pollen component does not change much with time and that the Holocene pollen spectra in peat samples do not differ significantly from those in surface samples; these findings are supported by our study reported here.

Previous studies on modern pollen assemblages from 11 lakes in Svalbard (Birks et al. 2004) showed the long-distance extra-regional pollen component (sensu Janssen 1984) contributes 2–25% to the spectra. Dorozhkina (2005) indicates that the Holocene pollen and spore spectra of the lake and peatbog sediments from Nurdamen Lake (Cape Fuglehuken, the most northern point of the Prince Charles Foreland) are in general formed by the local component as well as by Cyperaceae, Poaceae and bryospores, whereas the long-distance pollen component of the Pinus haploxylon type (i.e. subgenus Strobus) and P. diploxylon (i.e. subgenus Pinus) (sensu Millar 1998), is minor. Taking all this into account and assuming (despite several studies suggesting that wind strength and/or direction in the Arctic varied during the Holocene – see e.g. Park et al. 2018; Zhang et al. 2023) the wind conditions (i.e. speed and direction) in Svalbard during the studied period (i.e. the last ca 800 years) were relatively stable (Figure 3), a comparison of pollen studies performed in the Svalbard archipelago and adjacent isles since the 1970s supports the conclusion that the proportion of long-distance extra-regional pollen there is rather robust in both time and space (see Figures 5 and 7; and see the soil sample analysis presented in the Supplementary material: Figure S1).

Since the early palynological work in Svalbard, it has been known that the long-distance extra-regional pollen mostly consists of Pinus and Betula brought by the wind from northern Fennoscandia (Hyvärinen 1970; Surova et al. 1982, 1988; Birks 1991). Pinus is known as a massive pollen producer, and is a wind-pollinated group of plants as the vesiculate grains are designed to be easily translocated by aeolian and fluvial transport (Heusser and Balsam 1977; Heusser 1988). As for Betula, most (if not all) of its pollen must be also assigned to the long-distance component. In many cases, especially for pollen taxa of mixed and/or unclear origin, it is hard to distinguish at any level what portion of pollen comes from the regional or from the extra-regional source. In the case of Betula, however, in the high Arctic the picture is less complicated as the arboreal vegetation is absent here (for obvious reasons). Betula nana L. ssp. tundrarum (Perfil.) Á. Löve and D. Löve is rare in Svalbard but has its largest population in the south facing slope of Colesdalen (Engelskjøn et al. 2003, Alsos et al. 2004). It is regularly seen with both male and female catkins, so although no germinable seeds or seedbank have been found, it is expected to produce some pollen regularly (Alsos et al. 2002, 2003; Eidesen et al. 2007; Arnesen et al. 2014), in very small amounts. These factors suggest that the contribution of regionally produced pollen of Betula is tiny to negligible in Svalbard.

Alnus is a common component found in pollen diagrams of Svalbard (Hyvärinen 1970; van der Knapp 1988a; Birks et al. 2004; Jankovská 2017) and is present in proportions from 0.5% to almost 5% in the spectra of Reindalen (Surova et al. 1982) and Ny-Ålesund peat (Rozema et al. 2006). In our study, Alnus was found only in sediment samples older than 1960 CE, and is present in soil samples as single grains (Samples TE001 and Te006 Supplementary material: Figure S1).

Other arboreal pollen identified in the previous studies accords with our findings both in soil probes and in the sediment sequence from Tenndammen: Picea type is known from the lake sediments of Skinkevatna, Bjørnøya (Hyvärinen 1970); Juniperus type was identified in the Svalbard lake surface samples by Birks et al. (2004) and was distinguished in pollen caught with a Burkard pollen trap at Ny-Ålesund (Johansen and Hafsten 1988), where it forms about 10% of the extra-regional component together with Betula, Pinus and Alnus. A few grains of Corylus (Hyvärinen 1970; Surova et al. 1982; van der Knapp 1988a; Birks et al. 2004; Rozema et al. 2006; soil samples Te002), Carpinus type (Surova et al. 1982; van der Knapp 1988a; soil sample Te001, Supplementary material: Figure S1) and Quercus (Hyvärinen 1970; Birks et al. 2004; soil sample Te001) are regular findings in peats and in lacustrine sediments, but we only identified some isolated pollen grains of these trees in the soil samples. Ulmus (Hyvärinen 1970; Surova et al. 1982; Rozema et al. 2006; soil sample Te003, Supplementary material: Figure S1) was additionally registered as a single grain in the sediment of Te2019 (pollen zone IV, Figure 6). As these pollen types (i.e. Corylus, Carpinus type, Quercus/Fagus type, and Ulmus) are only present in our record as single grains, it is difficult to derive conclusions regarding what exactly brought them to the study site.
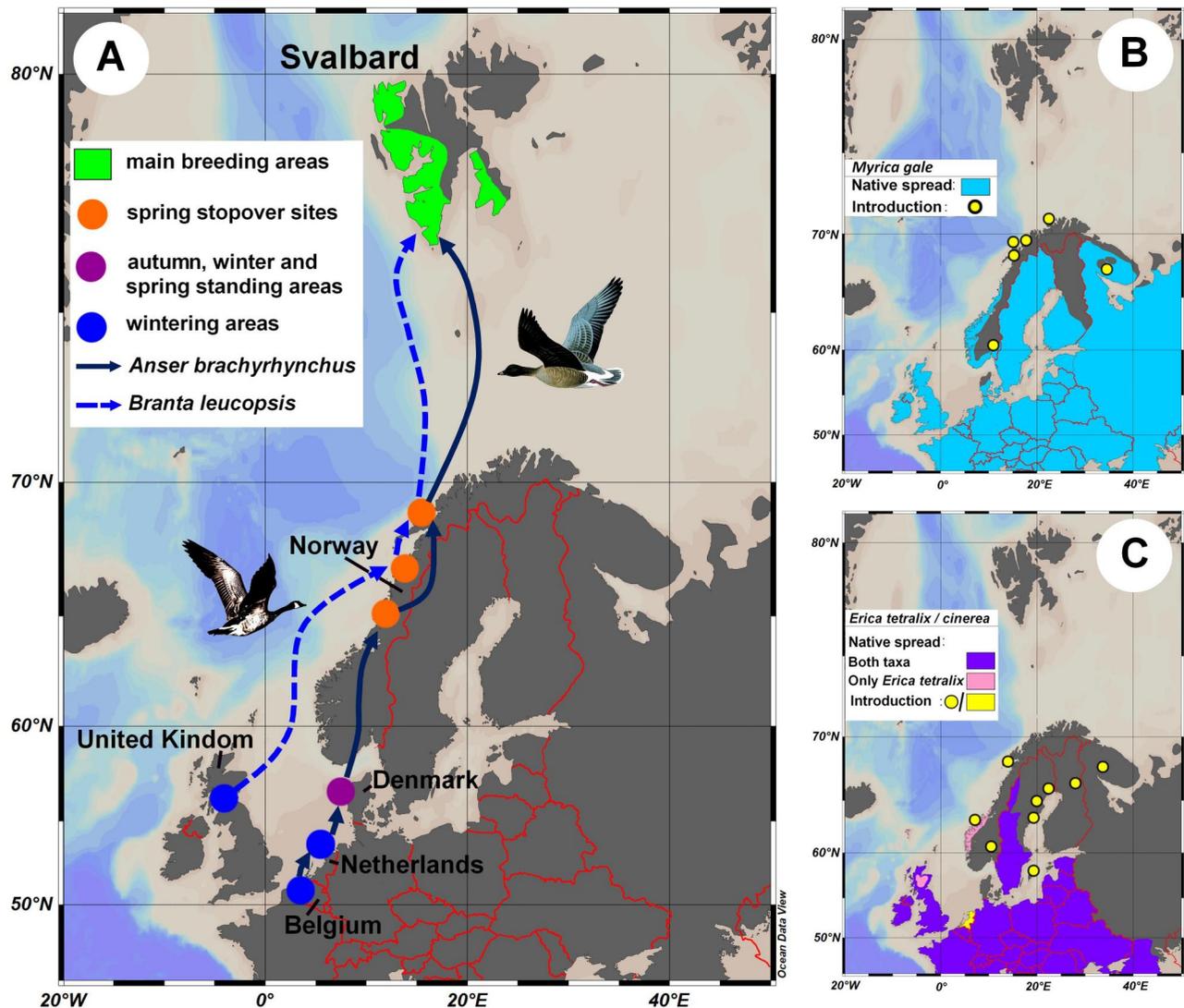
**Figure 8.** (A) Migration routes, wintering, spring and autumn grazing, and breeding areas of the geese *Branta leucopsis* and *Anser brachyrhynchus* with regard to the distribution of (B) *Myrica gale* and (C) *Erica tetralix/E. cinerea* since the beginning of the twentieth century. Maps were created by the first author of the publication using the licensed Ocean Data View software (academic license for A. Poliakova from 2013) and a base ground map available from: http://odv.awi.de. Patterns of bird migration are derived from Hessen et al. (2017) and plant distribution areas for Scandinavia - from Mossberg and Stenberg (1992), for the rest of Europe are retrieved from the "Plants of the World Online" website (https://www.powo.science.kew.org).

## 6.2. Exotic pollen; human and bird migration

Some interesting and unexpected findings were grains of subtropical and tropical pollen, i.e. *Acalypha* type, *Albizia/Mimosa* type, Amaryllidaceae type, *Eucalyptus* type, *Juglans* and *Passiflora* type. All of these plants (except *Acalypha* and *Eucalyptus*) are insect-pollinated and produce small amounts of pollen. *Acalypha* and *Eucalyptus*, in contrast, are large-scale pollen producers, although they naturally occur mainly in low latitudes and warm climates, and are commonly used as decoration plants in recreation parks and botanical gardens (e.g. Seberg 1984; Hill 1994; Webster 1994; Radcliffe-Smith 2001; Sagun et al. 2010; Stanturf et al. 2013; Macphail and Thornhill 2016). All the (sub)tropical pollen types were only found in the period between the 1930s and 1960s CE, which corresponds with the most intensive human activities in Colesbukta. The peak of coal mining occurred in the 1950–1980s (https://arcticugol.ru; Rose et al. 2004), and the most intensive human migration took place at that time. Based on

our knowledge of the history of the Soviet Union in 1930–1960s, Soviet legislation (e.g. Collection of Legislation and Orders of the RSFSR 2018), and a number of personal communications with retired miners of the former Grumant and Colsbay Mines of the Arktikugol Company, we assume that the most likely vector of exotic pollen transportation in Svalbard in the 1930s–1960s was associated with the shift-based work of the miners and supporting staff in Colesdalen. In that historical period, according to the USSR policy regarding medical services, all mining personnel and their family members used to have the right to 24-day long holidays with medical treatment (In Russian: санаторно-курортное лечение) on resorts in a warm climate, e.g. in the northern Caucasus and Crimea. As *Acalypha*, *Albizia/Mimosa* as well as plants of the family Amaryllidaceae and *Passiflora* are widely used as decorative plants in greenhouses and in parks because of their attractive flowers, and since *Eucalyptus* and *Juglans* are planted both in northern Caucasus and in the Crimea in the parks, botanical gardens and arboreta, it may
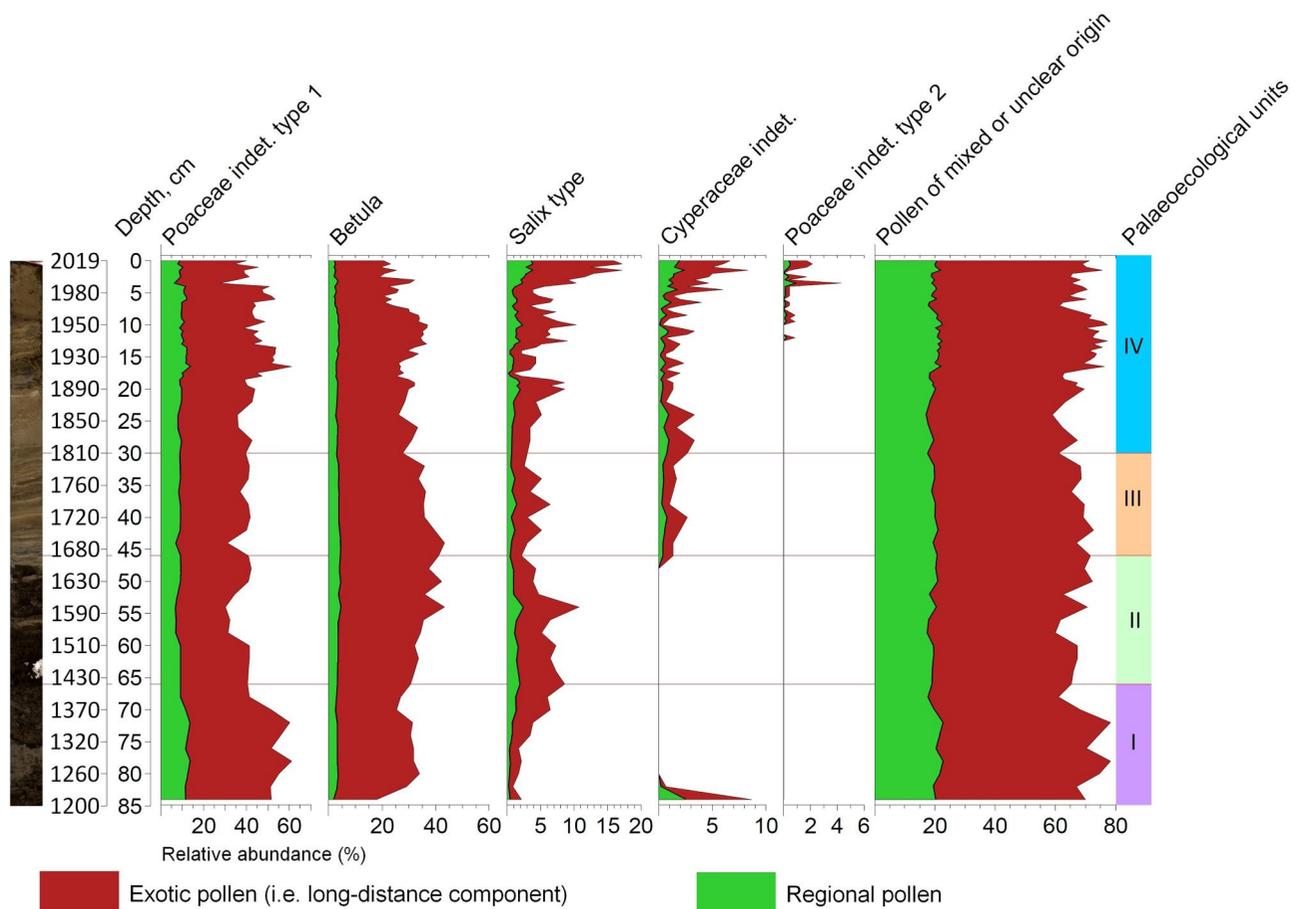
**Figure 9.** Re-calculated pollen diagram for pollen of mixed and/or unclear origin, showing assumed proportions of the regional (green) and extra-regional long-distance components (dark red). Only pollen types with abundances of 5% or greater are included.

be that their pollen was unintentionally collected by the visiting miners during their holidays and brought back to their working place, where it was washed off clothes into the soil and then into the lake. It is difficult to test this hypothesis with real data, but the nature of these plants, their natural distribution and the timing support this assumption. In contrast, the hypothesis of wind transportation of the exotic pollen fails as that pollen is only encountered in the sediments during the fixed period of ca 1930s–1960s CE, and the local wind patterns in the study area remained relatively stable throughout the studied period. (Compare the wind directions and wind frequency distribution presented in Figure 3 with those of the Russekollen during ca 1930s–1960s CE presented in the Supplementary material: Figure S5).

Two pollen types, namely the *Myrica* (*gale*) type and the *Erica* type, do not show any correlation with samples from the pollen zone Te2019-IV (Figure 6), and, therefore, their presence cannot be explained by human activity or human migration. Pollen of both taxa can be theoretically transported by the wind from North and Central Europe, where these plants are rather widespread (Figure 8). However, the closest source-area for both pollen types is northern Norway, where *Myrica* and *Erica* not only have been introduced as decorative plants, but also grow naturally in small amounts (Mossberg and Stenberg 1992) Both taxa are also known from the natural ecosystems of Sweden, Denmark and Finland (the Plants of the World Online: https://www.powo. science.kew.org) However, since neither of these two pollen types is mentioned in other sites from Svalbard and nearby isles, it is suggested that a local factor could be responsible for the presence of *Myrica* (*gale*) and *Erica* pollen in Colesdalen.

Tenndammen is highly attractive to birds, and the chironomid stratigraphies from that lake show a primary correlation with the gradient in chlorophyll *a* values, human activity, and bird presence (Birks et al. 2004 and Figure 4b and c within). Further, genetic analyses of plants suggest that birds have contributed to dispersal of plants in Svalbard and other Arctic regions (Alsos et al. 2007, 2015). Our visual observations during the fieldwork in September 2019 revealed massive amounts of barnacle-goose (*Branta leucopsis*) grazing at the research area. Both the barnacle-goose and the pink-footed goose are common in Svalbard (https://www.npolar.no/en/species/), and the overlap in their main breeding areas is in the Colesdalen and on the shores of Lake Tenndammen (Hessen et al. 2017; Figure 8A).

The barnacle-geese spend their wintering season in the British Islands, i.e. in the Solway Firth at the border of England and Scotland, whereas the pink-footed geese winter in Denmark, the Netherlands and Belgium. Their migration routes lead southwards via the Norwegian mainland to their autumn staging areas in Denmark and in the Netherlands. As Figure 9B and C demonstrate, *Myrica gale* and *Erica* plants are both present in the mentioned areas, at wintering sites and at autumn/spring staging spots.

Moreover, in the winter grazing areas of *Branta leucopsis* in Scotland, *Erica cinerea* is an 'iconic flower' (e.g. Khela 2013). In the Netherlands, where *Anser brachyrhynchus* spends winters, *Erica cinerea* is an introduced honey and ornamental plant largely used in parks and gardens. In Belgium, *Erica* is a native plant (https://powo.science.kew.org/). Keeping in mind a constant and random presence of *Myrica* (*gale*) and *Erica* pollen types in the Te2019 core (Figure 5) sediments as well as in the soil samples (Supplementary material: Figure S1), we hypothesise that these pollen in Svalbard may originate in the wintering sites and the autumn/spring staging locations of the migrative birds and are likely to have been brought to the Colesdalen by these birds.

### 6.3. Regional pollen

Surova et al. (1982) have shown that pollen spectra in Reindalen and Adventdalen are composed of regional pollen and spores. The latter were identified as *Lycopodium* (or, according to modern systematics, *Huperzia selago*) and Polypodiaceae. Dai and Weng (2011) additionally indicated that it is hardly possible for the spores of ferns to be transported by air over long distances, as it is difficult for the wind to pick them up from the wet sticky soil, while water can easily wash them out. This suggests that for spores water (not air) has to be considered a primary translocation medium, especially if we consider the typically damp and rainy conditions during the vegetation season in Svalbard. However, the role of air in spore transportation should not be dismissed completely. The transport and relocation of pollen and spores is a complicated process as, on the one hand, turbulence conditions that initialise the movement of particles can have an impact on particle dispersal distances, e.g. by lifting particles above the vegetation canopy layer (Nathan and Katul 2005); and, on the other hand, they can disperse in the upper parts of the atmospheric boundary layer and also may be affected by up- and downdrafts (Boehm and Aylor 2005).

It is also known that pollen grains and spores typically become aggregated (Di-Giovanni et al. 1995), so the effective size of particles may vary considerably. Dispersal models (Di-Giovanni et al. 1989; Okubo and Levin 1989; Di-Giovanni and Beckett 1990; McCartney and Lacey 1991; Aylor and Flesh 2001; Nathan et al. 2002; Jarosz et al. 2004; Soons et al. 2004; Kuparinen et al. 2007) have been suggested for studying and predicting pollen dispersal distance. The models show that only a few factors influence the pollen dispersal process: release height (as a pollen particle released from the top of the canopy would be taken up into the air more readily and be more easily carried by the wind) and the size of the pollen (lighter particles are more easily taken up). Turbulence in the mixed layer of the air is shown to be a relevant influencing factor only at horizontal distances >1000 m. Specifically, stable atmospheric stratification in the models clearly differs from the other scenarios (Kuparinen et al. 2007), but pollen are mainly released during daytime (Jackson and Lyford 1999; Jarosz et al. 2003), whereas stable stratification is an event more typical of night time, and is, therefore, not highly relevant for pollen dispersal. Other empirical and modelling studies (e.g. Tackenberg 2003; Schueler and Schlünzen 2006) suggest that the dispersal process not only at a local scale but also at regional dimensions must be considered.

All the discussed issues suggest it may be highly likely that our results and previous findings regarding pollen of *Erigeron* type, *Arnica/Taraxacum* type, *Cerastium* type, *Campanula* (*rotundifolia*) type, *Dryas* (*octopetala*) type, *Papaver* (*dahlianum*) type, *Pedicularis* (*hirsuta*) type, *Polemonium* (*boreale*) type, *Bistorta* (*vivipara*) type and *Koenigia islandica* type, most large-grained Ericaceae (i.e. *Cassiope* type, *Vaccinium* type and Ericaceae indet.) and Saxifragaceae pollen (i.e. *Micranthes nivalis*, *Saxifraga cernua* type, *Saxifraga cespitosa* type, *Saxifraga oppositifolia* type) come from source vegetation locally and regionally but not outside of Svalbard. All in all, Svalbard is an archipelago in the sea, and in order to get there, pollen must travel many kilometres (at least 960 km from the closest land, i.e. the Norwegian coasts; see https://toposvalbard.npolar.no). Transport of pollen grains over such a long distance requires several preconditions. First, the long-distance source area must be favourable for both the emission of pollen in the air and its uplift to a sufficient air altitude. Second, pollen must remain in the air through the whole journey without being aggregated with other particles and sinking into the sea on its route towards the study site. It is known that the deposition of pollen happens when downward air movements are associated with rain of 0.5 mm/h (Rousseau et al. 2003). Third, pollen grains must not be damaged during transportation. All this, and the facts that those source plants produce little pollen and, being insect-pollinated, do not disperse much pollen via wind, suggests a regional origin for the mentioned pollen types, although a contribution by long-distance transport cannot be rejected completely.

### 6.4. Pollen of mixed and/or unclear origin

According to our results from the core Te2019 and the 10 soil samples as well as from the analysis of previous pollen studies from 1960 to 2021, exotic pollen in Svalbard accounts for about 25 to 32% of the total (mean of 29%, Figures 5 and 9). This suggests that pollen spectra in Svalbard are quite robust. If we assume this finding is correct and apply it proportionally, to recalculate pollen percentages for pollen with mixed and/or unclear origin (Figure 9), we would estimate that about 10% of Poaceae pollen and up to 5% of *Salix* and Cyperaceae probably has a regional origin. Regionally produced pollen of *Betula* remains at around 1% of total *Betula* pollen and less than 1% of the total pollen sum (Figure 9). For Brassicaceae indet., Caryophyllaceae indet., *Juncus* type, Polygonaceae indet., Saxifragaceae indet. and *Ranunculus* type, a re-calculation of abundances is impossible to apply as percentages of these pollen types are too low (1–2%, Figure 9).

## 7. Summary and concluding remarks

Lacustrine sediment samples from Svalbard, Colesdalen valley, and Lake Tenndammen, as well as 10 soil samples collected from the lake's shores at ca 2–4 m from the water, were studied for pollen and spore analysis with an emphasis on the long-distance component and potential sources of pollen. This research provides a first examination of the long-distance component problem in Svalbard palynology, and demonstrates how the history of human occupation and transmigration can be directly reflected in lake sediments, as summarised in the following conclusions:

- From ca 1200 CE to the present, the contribution of regional pollen, long-distance extra-regional pollen, and pollen of mixed or unclear origin in Colesdalen remained relatively stable, at about 1%, 29%, and 70%, respectively.
- For informative pollen analysis, the minimum required pollen count in Svalbard lies between 80 and 100 pollen grains, as grains of exotic origin are largely found thereafter. To catch all varieties of rare exotic pollen types, counts exceeding 200 pollen grains would be recommended.
- The pollen concentration in the sediments is typically very low; thus, material requires concentration.
- The taxonomical diversity of pollen spectra increases through the time period from 21 to 56 types, in terms of both regional (increasing from eight to 21 types) and exotic pollen (increasing from five to 12 types).
- The taxonomical diversity of exotic pollen is strongly correlated with human activities in the region. Pollen spectra reflect human industrial history in Colesdalen.
- Three main vectors of exotic pollen transport are suggested: long-distance wind transportation, bird migration, and human migration.
- Pollen of Apiaceae, Fabaceae, Saxifragaceae, *Campanula*, Rosaceae, *Papaver*, and *Polemonium* (*boreale*) type most likely originates from the regional vegetation.
- About 10% of Poaceae pollen, and up to 5% of *Salix* and Cyperaceae, is of regional origin. Regionally produced pollen of *Betula* is negligible and only locally important.
- For Brassicaceae indet., Caryophyllaceae indet., *Juncus* type, Polygonaceae indet., Saxifragaceae indet. and *Ranunculus*, the source vegetation remains unclear.
- Pollen of *Myrica* (*gale*) type and *Erica* type are explained by the seasonal migration of geese from Scotland (UK), Belgium and the Netherlands.
- Other exotic pollen, including *Ulmus, Juglans*, and unexpected tropical pollen of *Albizia/Mimosa* type, *Eucalyptus* type, *Acalypha* type, and *Passiflora* type, are found in the sediments exclusively during the 1930s–1960s, in the period associated with the most intensive mining activity and human migration to and from Colesdalen, including holiday-associated migration to the sub-tropical regions and resorts of the former USSR.

## Disclosure statement

No potential conflict of interest was reported by the authors.

## Notes on contributors

*Anastasia Poliakova* is palaeoecologist and data analyst. She received her PhD from the Georg-August University in Göttingen, Germany, and has 15 years of research experience participating in international research projects focused on modern and past multiproxy vegetation studies; the history of Arctic, European, subtropical and tropical vegetation; land use; and palaeoenvironmental reconstruction. In this project she was focused on the human-induced changes in the landscapes, environments, and vegetation of the high Arctic, combining methods of classical vegetation science and palaeoecology with ancient DNA sediment studies, diverse methods of data analysis and bioinformatics. She designed and performed this study.

*Antony G. Brown* is an experienced palaeoecologist with over 40 years of practice who has worked in many environments from the tropics to the Arctic. A particular area of his research related to this paper has been the transport and taphonomy of pollen. His broad interests are palynology, human–environment interaction and, most recently, the applications of *seda*DNA to archaeology. He has published over 200 academic papers and several books and is a fellow of both the Geological Society of London and the Society of Antiquaries.

*Inger G. Alsos* has 30 years' experience on the ecology of Artic plants. She is the leader of the Aurora Centre of Arctic Ecosystems Genomics (ArcEcoGen), UiT – Arctic University of Norway. Her research focuses on the past and likely future distribution of Arctic and subarctic vascular plants. She has combined genetic data (modern and ancient DNA), species distribution modelling, and fossil data to explore dispersal routes, colonisation frequencies, and long-term effects of climate change on northern ecosystems. She is currently working on ancient DNA in lake sediments from Iceland, Svalbard, Northern Fennoscandia, Northern Russia, Greenland, and the Alps, as well as a full-genome reference library for the Norwegian and polar flora (PhyloNorway).

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## Data availability statement

Data are available from the following sources:

Poliakova, Anastasia; Brown, Antony G; Alsos, Inger G. (2022): Raw counts of pollen and spores for the sediment core Te2019 (Svalbard, Colesdalen valley, Lake Tenndammen (N 78°06.118; E 15°02.024) and for 10 soil samples collected from the lake shores. PANGAEA, https://doi.pangaea.de/10.1594/PANGAEA.942567.

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Poliakova, Anastasia; Brown, Anthony G; Sanderson, David C W; Cresswell, Alan J; Håkansson, Lena M; Goslar, Tomasz; Alsos, Inger Greve (2022): ¹⁴C datings of sediment core Te2019. PANGAEA, https://doi.pangaea.de/10.1594/PANGAEA.941940.

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