







Dispersal of pollen and invertebrates by wind in contrasting Arctic habitats of Svalbard

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Abstract: Although Svalbard archipelago is considered as a natural laboratory for the environmental studies in the High Arctic, the knowledge on the transport and diversity of bioaerosols (aeroplankton) in the atmosphere is poorly recognized. To improve our knowledge about the aeroplankton over the Svalbard, we conducted a short-term study in the central part of the archipelago with a special focus on two important, but understudied in this region, airborne components: pollen grains and invertebrates. Aerobiological traps, three impact-type samplers and 12 pitfall-type water traps, were operated for a week of July 2022 at three sites located near Longyearbyen, the largest settlement of Svalbard. These sites, that is, Platåfjellet, Longyearbreen Glacier, and glacier valley, varied in the local sources of biological material and altitude. In total, 11 pollen taxa were isolated from pollen impactors. Most of them (68%) belonged to non-native plants, for example, *Alnus* sp., *Betula* sp., *Picea abies*, or *Pinus sylvestris*-type pollen. In pitfall-type water traps, we found invertebrates representing Acari (Prostigmata, Endeostigmata and Oribatida), Collembola (*Agrenia bidenticulata*), Tardigrada (Eutardigrada) and Rotifera (Bdelloidea). The most taxa-rich site, both for pollen and invertebrates, was Platåfjellet, characterized by open landscape dominated by small cryptogams, mainly lichens and mosses, and sparse patches of vascular plants. Even though our sampling was short-term, we found diverse taxa



belonged to native and alien species, indicating that both local and long-range transport shape aeroplankton composition and seeding of Arctic habitats. Long-term aerobiological monitoring in diverse ecosystems of Svalbard is needed to understand spatio-temporal influence of aeroplankton on ecosystems.

Keywords: Arctic, Spitsbergen, bioaerosols, alien species, long-range transport.

Introduction

Bioaerosols, also known as aerosols of biological origin or aeroplankton, have a vital role in sustaining the balance of the global ecosystem (Fröhlich-Nowoisky *et al.* 2016). Interactions between bioparticles released from the biosphere into the atmosphere shape both abiotic and biotic systems. These connections include the colonization of newly formed ecosystems, the reproduction and spread of organisms, microbial species turnover (*e.g.*, after snow-melt), support of the nutrient-poor environments, such as glaciers, and ultimately the enhancement of animal, including human, and plant diseases (Fröhlich-Nowoisky *et al.* 2016; Šantl-Temkiv *et al.* 2018; Malard *et al.* 2023). Therefore, monitoring bioparticles is of high importance across time and space at various spatial scales, for example, to understand the mechanisms and characteristics of global atmospheric “traffic” (Smith 2013).

Due to Arctic amplification, which leads to larger temperature changes in the Arctic region compared to the rest of the Earth, northern regions are experiencing severe changes. These changes include shifts in atmospheric circulation and wind patterns, as well as the rapid melting of ice and snow cover, which exposes new barren rocks and soils (Serreze and Barry 2011; Strzelecki *et al.* 2020; Ignatiuk *et al.* 2022).

Therefore, the Arctic appears to be a robust study site for investigating the synergistic effects of changing atmospheric circulation, increasing temperatures, and the colonization of native and alien species in terrestrial ecosystems using aerobiological approaches. Indeed, atmospheric transport plays an important role in shaping biological communities in remote areas, such as the Arctic (Pearce *et al.* 2010). Moreover, the relatively simple polar ecosystems, characterized by strong seasonality, simple trophic networks, and the recent formation of new ecosystems in ice-free areas, are considered valuable for studies on ecosystem functions. These studies encompass succession processes as well as the impact of alien species on native flora and fauna across a wide range of habitats (Adams *et al.* 2006; Coulson 2013; Gwiazdowicz *et al.* 2020).

The Svalbard archipelago is known as natural laboratory for the environmental studies of Arctic ecosystems (Coulson 2013). This region is characterized by a network of meteorological stations, long-term environmental

monitoring in terrestrial, glacial, and marine ecosystems, which provide baseline for studies on the spatial distribution of animal and plant communities (Coulson *et al.* 2014; Smoła *et al.* 2017; Hop and Wiencke 2019; Ignatiuk *et al.* 2022). Svalbard is one of the most climatically sensitive regions in the world, drawing the interest of scientists as an environmental reference for Arctic amplification (Rogers *et al.* 2005). According to The State of Environmental Science in Svalbard Report 2022, the studies on the impurities over the Svalbard, which integrate the chemical, biological, and physical approaches, are crucial for anticipating the role of aerosols in polar ecosystems (Gevers *et al.* 2023). Expanding the spectrum of aerobiological sampling is particularly important, as a more in-depth characterization of aeroplankton biodiversity is currently lacking (Kozioł *et al.* 2023). Therefore, we focused on the diversity of the two components of aeroplankton: pollen grains and invertebrates belonging to micro and mesofauna. Both of them could be subjected to long-range transport (LRT) by air masses or passively transported by humans. Under favorable circumstances, these factors could impact the genetic variation of the native population or, in the case of animals, establish new populations in remote sites, far from their original distribution (Greenslade and Convey 2012; Coulson *et al.* 2013; Bartlett *et al.* 2021).

In polar regions, spores and invertebrates are colonizers of recently emerged ice-free glacier forefields and moraines, contributing to the establishment of new ecosystems (Ingimundardóttir *et al.* 2014; Gwiazdowicz *et al.* 2020; Wietrzyk-Pełka *et al.* 2020, 2021). Moreover, the transport of pollen and invertebrates across glacier surfaces could provide an additional payload of nutrients for microbial communities in these nutrient-poor habitats (Hotaling *et al.* 2021). Finally, tracking the sources and fate of pollen and invertebrates is much easier than those of procaryotes, which have complex and often untraceable origins (Yoo *et al.* 2017; Xie *et al.* 2021).

Only a few studies have covered the analysis of pollen in the troposphere over Svalbard. Notably, Polunin (1955), van der Knaap (1987), and Jędryczka *et al.* (2022) identified exotic pollen taxa within the Svalbard archipelago, including pollen from *Pinus* sp., which suggest the influence of long-range transport on the Svalbard environment. In contrast, Johansen and Hafsten (1988) detected pollen grains at Ny-Ålesund, and most of them were of local origin. The diversity of micro and mesofauna of this Arctic region is relatively well known comparing to other archipelagos (Coulson *et al.* 2014). Some studies investigated their transport by migratory birds, humans, or imported soils (Coulson *et al.* 2013; Pilskog *et al.* 2014), and only a few projects focused on the aerial transport of invertebrates (Hodkinson *et al.* 2001; Coulson *et al.* 2002, 2003; Coulson 2015). Among them, only two studies tested direct transport in the air (Coulson *et al.* 2002, 2003).

In this study, we used impact-type samplers and pitfall-type water traps installed above the surface of soil in three contrasting sites within the

Longyearbyen area: Platåfjellet, Longyearbreen Glacier, and glacier valley. The main aim was to enhance our understanding of pollen and invertebrates transport in the atmosphere, and to explore the potential for aerobiological investigations in central Spitsbergen, Svalbard archipelago.

Study area

The Svalbard archipelago is located between the Greenland Sea to the west, Barents Sea to the east, Norwegian Sea to the south, and Arctic Ocean to the north. Topography of this Arctic region is predominantly mountainous with many glaciated fjords. The climatic conditions of Svalbard are shaped by high latitudes, the circumpolar atmospheric circulation, and the circulation of ocean currents of the North Atlantic (Zwoliński 2013). The prevailing wind direction over the archipelago is from the east as a consequence of its relative location to the low-pressure systems in the Norwegian Sea (Isaksen *et al.* 2016). Svalbard was covered by extensive ice sheets several times in its geological history. During the last ice age, almost the entire archipelago was covered by an ice sheet (Lønne and Lyså 2005). Currently, over half of the land in Svalbard is covered by glaciers and ice sheets. The forefields are strewn with cryptogams, *i.e.*, lichens and plants that reproduce by spores, vascular plants, or covered by mature tundra, depending on the age of deglaciation and physicochemical parameters of soil (Nuth *et al.* 2013; Wietrzyk-Pełka *et al.* 2020, 2021).

Spitsbergen is the biggest island in the Svalbard archipelago, situated at 74°81'N and 10°30'E. The study area is located in the central part of the island (Fig. 1A), thus, the climate is more continental, drier and with a lower mean annual air temperature than in the remaining territory (Przybylak *et al.* 2014). Frequent yet low rainfall and average temperatures from -11.7°C in winter to $+5.2^{\circ}\text{C}$ in summer (1981–2010, Svalbard Airport weather station) are typical of this region. According to Osuch and Wawrzyniak (2017), the mean air temperature during the period of 1979–2014, recorded at Svalbard Airport, was -4.5°C , with February being the coldest month (average -13.9°C) and July the warmest (average $+6.4^{\circ}\text{C}$). For the July (1991–2021), the average temperature was $+4.7^{\circ}\text{C}$, precipitation 40 mm, and humidity 80% in the area of Longyearbyen (<https://en.climate-data.org/europe/norway/svalbard/longyearbyen-27870>). Throughout the study period, winds from the west and east prevailed, with wind speeds ranging from 1 mph to 19 mph (<https://weatherspark.com/h/m/148359/2022/7/Historical-Weather-in-July-2022-at-Svalbard-Airport-Longyear;-Svalbard-&-Jan-Mayen>). The vascular flora of Spitsbergen is dominated by grasses (*e.g.*, genera like *Festuca*, *Poa*, and *Puccinellia*), sedges (*Carex* sp.), rushes (*Juncus* sp.), wood-rushes (*Luzula* sp.), some herbaceous plants (*e.g.*, *Saxifraga* sp., *Silene* sp., *Draba* sp., and *Ranunculus* sp.), and shrubs (*Dryas octopetala* L. and *Salix* sp.) (Elven and Elvebakk 1996; Borysiak 2013).

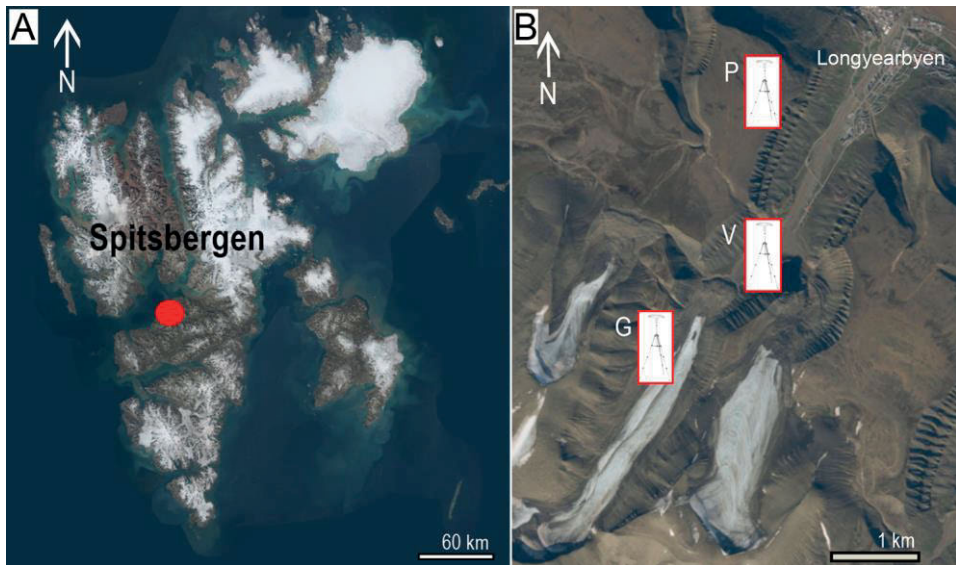


Fig. 1. Svalbard archipelago with sampling area indicated by red dot (A), and marked sampling locations (B): P – Platåfjellet; G – Longyearbreen Glacier; V – Valley. Adopted from <https://toposvalbard.npolar.no>.

Methods

Trap locations. — Aerobiological monitoring was conducted at three sites located near Longyearbyen (Svalbard): Platåfjellet ($78^{\circ}12'N$, $15^{\circ}34'E$, *ca.* 430 m a.s.l.) – abbreviated P, Longyearbreen Glacier ($78^{\circ}11'N$, $15^{\circ}30'E$, *ca.* 350 m a.s.l.) – abbreviated G, and valley ($78^{\circ}11'N$, $15^{\circ}33'E$, *ca.* 165 m a.s.l.) – abbreviated V on Fig. 1B. Platåfjellet (Mount Plateau) is a wide flat area (plateau) located to the west of the city. It is mainly covered by rocks and stones, with sparse vegetation – predominantly mosses and lichens, and scattered vascular plants hidden between rocks, for example, *Salix polaris* Wahlenb., *Saxifraga hiperborea* Brown, Chlor. Melvill., *S. cernua* L., *Micranthes nivalis* (L.) Small, *Pedicularis hirsuta* L., *Luzula confusa* Lindeb., *Cerastium* sp., and *Draba* sp. (own observations). Longyearbreen Glacier is a small cold-based valley glacier with northern exposition (Hodson *et al.* 2010). The sampling site was located on the lateral moraine *ca.* 5 m from the debris-free ice surface, and was characterized by exposed bare rocks covering ice, devoid of vascular plants and bryophytes. The third sampling site was located on a high embankment in the glacier valley around 1 km from the glacier. Within a radius of several dozen meters, the area was free of flowering plants. The nearest rich and compact cluster of vascular plants was located about 50 m to the east, near the former kennel. However, the bryophytes were common. The monitoring was conducted from 19th to 24th of July 2022, *i.e.*, six days in total.

Pollen and invertebrate collection. — The airborne pollen grains were collected with three impactors similar in design to pollen trap developed by Blackley (1873). In short, each impactor contained four upright microscope slides coated with standard adhesive (silicone) in accordance with the recommendations of European Aerobiology Society (Galan *et al.* 2014). The slides were attached to the walls of the cuboid in such a way that each slide faced different points of the compass. The microscope slides were protected from rain by a cover (Fig. 2A, B). After the sampling, slides were mounted using glycerine-gelatine media stained with fuchsine and closed with cover slides. All slides were investigated with light microscope (400x). Whole slide area was investigated and pollen grains number was expressed as pollen grain per slide (pollen/slide). Since the exact volume of air reaching the trap could not be determined, it was not possible to calculate the exact pollen concentration as with standard volumetric methods (Galan *et al.* 2014). Invertebrates were collected to 12 pitfall-type water traps, four traps per site (Fig. 2C), installed between stones 20–30 cm above the ground surface.

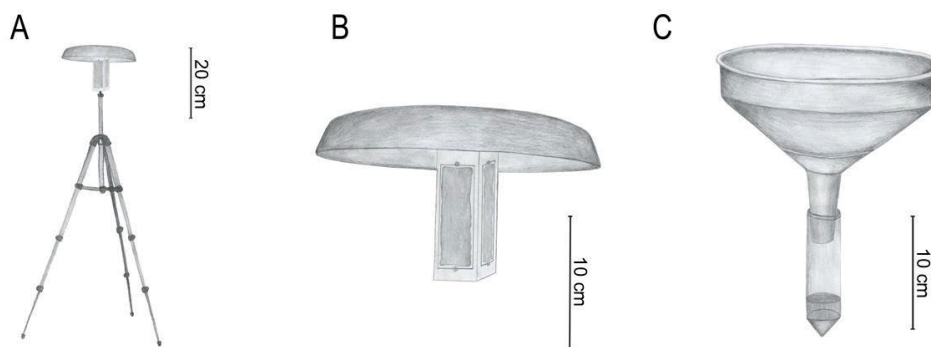


Fig. 2. Pollen trap (A, B) and pitfall-type water trap (C).

Air mass back trajectory and atmospheric dispersion modelling. — Backward air mass trajectories were calculated using the Hybrid Single Particle Lagrangian Integrated Trajectory model (HYSPLIT) (Stein *et al.* 2015; Rolph *et al.* 2017). Global Data Assimilation System (GDAS) meteorological data with a spatial resolution of $0.25^{\circ} \times 0.25^{\circ}$ were applied. HYSPLIT trajectories were calculated 72 hours back in time with two-hour steps between each trajectory, *i.e.*, 12 trajectories each day, for every day between 19th and 24th of July 2022. Three starting heights of back-trajectories: 500 m, 1000 m, and 1500 m have been chosen, to take into account variations in air mass directions with increasing altitude. The particle dispersion modelling analysis within HYSPLIT was applied to verify whether pollen released from potential source areas (indicated by backward air mass trajectories) could reach Svalbard. We calculated the forward HYSPLIT dispersion of particles with a settling velocity of 0.012 cm s^{-1} which is the mean value estimated for birch pollen, here chosen as a model pollen (Jackson and Lyford 1999; Sofiev *et al.* 2006). The simulations were performed

using GDAS $0.25^{\circ} \times 0.25^{\circ}$ resolution meteorological data. The modelling parameters were as follow: (i) particle release starting time – every day at 12:00 between 16–22 July 2022; (ii) release duration – eight hours; (iii) the release top and bottom heights – 15 m and 1 m, respectively, to indicate the release of pollen from trees/shrubs; (iv) runtime parameters – 72 hours, with an averaging period of eight hours and a top of averaged layer of 500 m a.g.l. As the exact release quantity of pollen was unknown, the parameter was set up to one unit of mass (according to HYSPLIT instruction), so the resulting concentrations represent a dilution factor ($1/\text{m}^3$) instead of true air concentrations, and provide a “footprint” of the dispersion pattern.

Invertebrate identification. — The mite specimens were mounted on microscopic slides in Hoyer’s medium and examined with PC microscope Olympus BX50. The photographs were taken with the aid of a digital SLR camera attached to the DIC microscope Olympus BX51. The specimens were identified to the family-level using the key by Krantz and Walter (2009) and subsequently to the genus- or species-level using the keys by Pritchard and Keifer (1958), Strandtmann (1971), Zacharda (1980), Uusitalo (2010), Khaustov (2014), and Hernandez *et al.* (2016).

Springtails were identified to the species level with taxonomic key by Potapov (2001). One specimen was identifiable only at family level, because of the bad state of preservation and the juvenile stage. Specimens were preserved at -20°C in 75% ethanol. For slide preparation, they were cleared by a short immersion in 10% KOH solution, and then, they were passed in Chloralphenol. Finally, they were mounted on slides using Swann medium as preservative solution (Rusek 1975). Tardigrada were mounted in Hoyer medium and identified according to description by Kaczmarek *et al.* (2018). Bdelloid rotifers were not identified.

Results

Pollen. — In total, 95 pollen grains, belonging to 11 taxa of plants at various taxonomic levels, *i.e.*, species/genus and family, were counted. Unidentified pollen, for instance, damaged, crushed, and fragmented grains, constituted 22% of all pollen. Further analyses concern only identified pollen grains, 74 grains in total.

Most of pollen (68%) belonged to non-native plants, that is, *Alnus* sp., *Betula* sp., *Juniperus communis* L., *Picea abies* (L.) Karst, *Pinus sylvestris*-type pollen, and *Urtica* sp. (Fig. 3). The following taxa were included in the group of the native pollen grains: *Saxifraga* sp., *Cerastium* sp., *Salix* sp., *Oxyria digyna* (L.) Hill., and Poaceae. The most common pollen taxa were *Betula* sp., Poaceae, *Pinus sylvestris*-type pollen, and *Cerastium* sp.; 34%, 12%, 9%, and 9%, respectively (Fig. 4). The highest number of pollen grains was isolated from Platåfjellet (53%), while the lowest on Longyearbreen Glacier (21%), where, additionally, only non-native pollen grains were observed (Fig. 5). We did not observe any clear differences

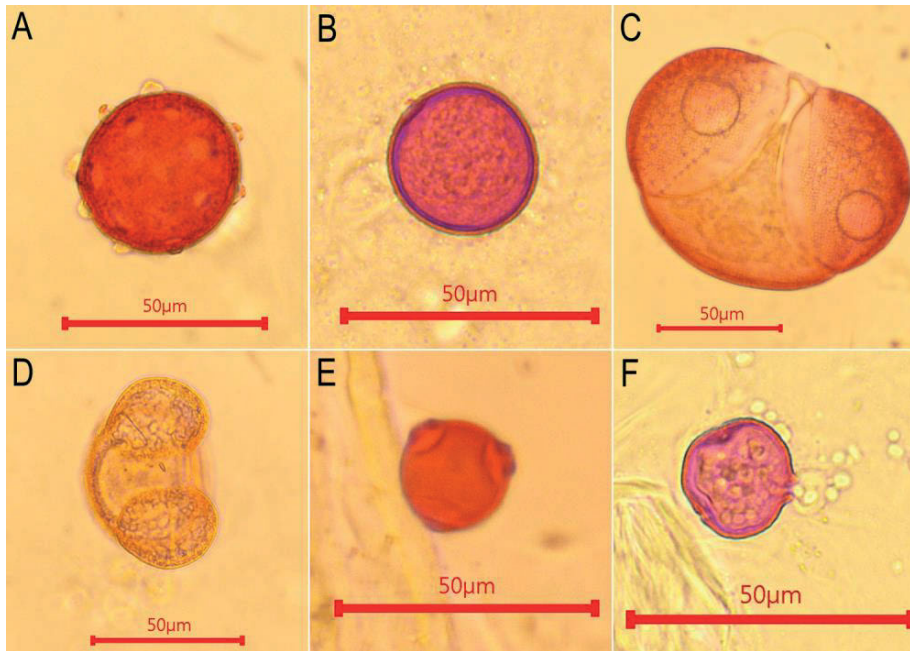


Fig. 3. Examples of pollen grains collected in the air, vicinity of Longyearbyen: (A) *Cerastium* sp., (B) Poaceae, (C) *Picea abies*, (D) *Pinus sylvestris*-type pollen, (E) *Betula* sp., and (F) *Oxyria digyna*.

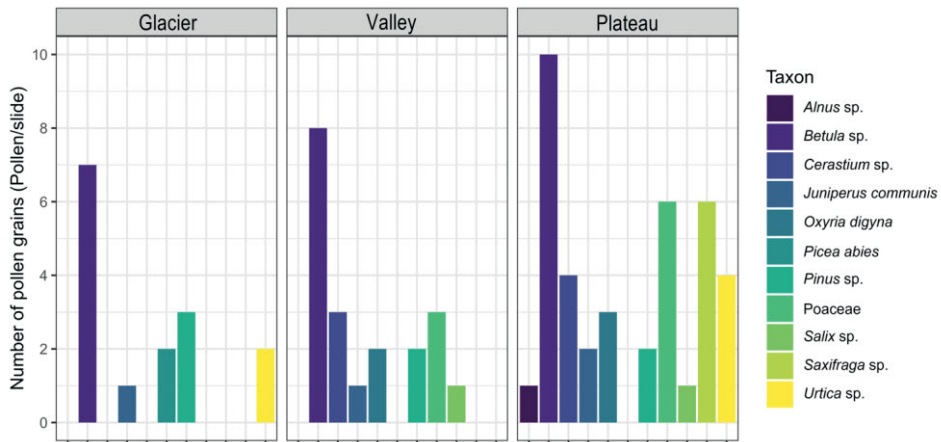


Fig. 4. Pollen grains collected at three monitoring stations.

between the number of pollen grains deposited on slides facing different directions of the world; however, the highest number of pollen grains was deposited at Platåfjellet on slide directed to the south, *i.e.*, 16% (Fig. S1).

Air mass back trajectory analysis revealed that, during the collection period, the air masses were originating from south (20th and 21st of July), south-east (19th, 22nd, and 23rd of July) and east (24th of July) (Fig. 6). The most distinct

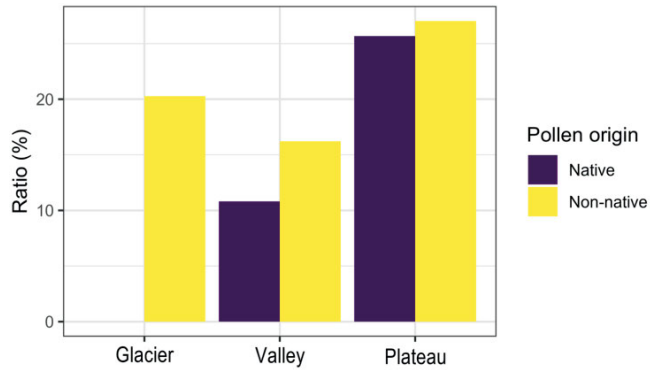


Fig. 5. Native and non-native pollen grains collected at three monitoring stations.

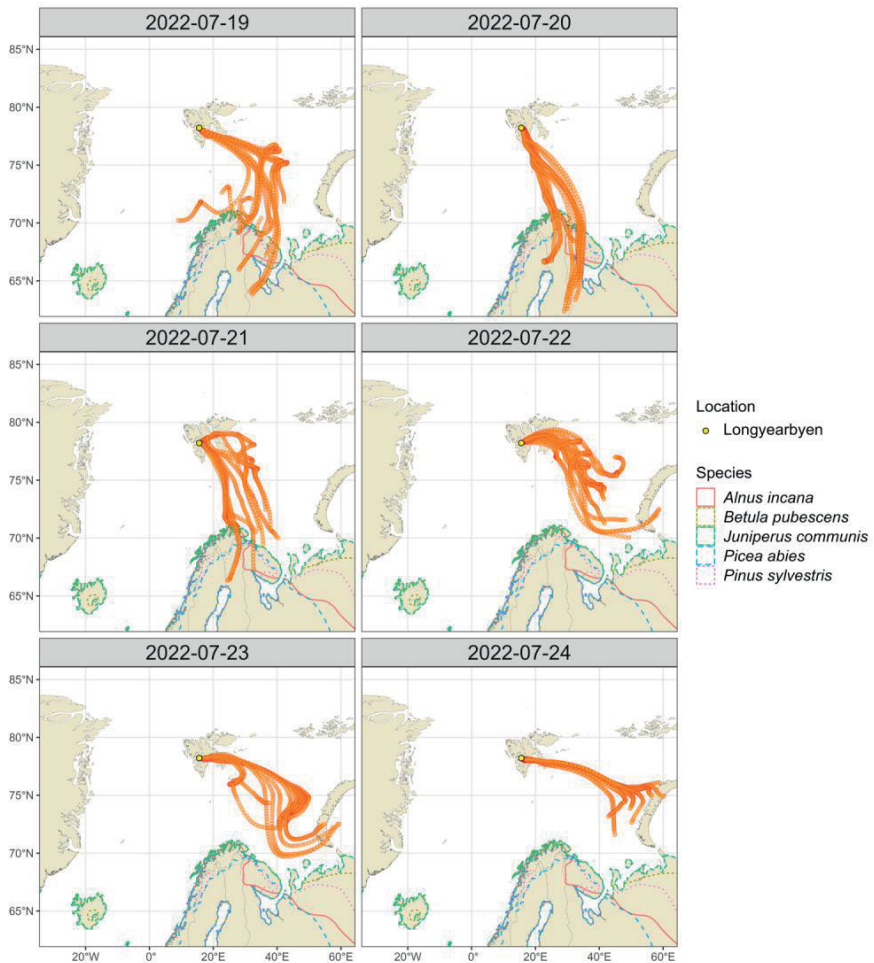


Fig. 6. Air mass back trajectory analysis (calculated by HYSPLIT model) showing the air mass movement to Longyearbyen between 19–25 July 2022 (starting height: 1000 m, duration: 72 hours).

pathways, characterized by compact uniform trajectories, were observed on 20th and 24th of July. During these days, the air masses were approaching from Northern Scandinavia and Novaya Zemlya, respectively. The vegetation on Novaya Zemlya largely consists of Arctic tundra, thus lacks tree species (Tishkov 2012), unlike Northern Scandinavia. The HYSPLIT particle dispersion analysis showed that both birch and pine pollen released from the central part of Northern Scandinavia on 18th July at 12:00 would reach Svalbard within 48–56 hours, which is consistent with the results of the backward air mass trajectory analysis (Fig. 7).

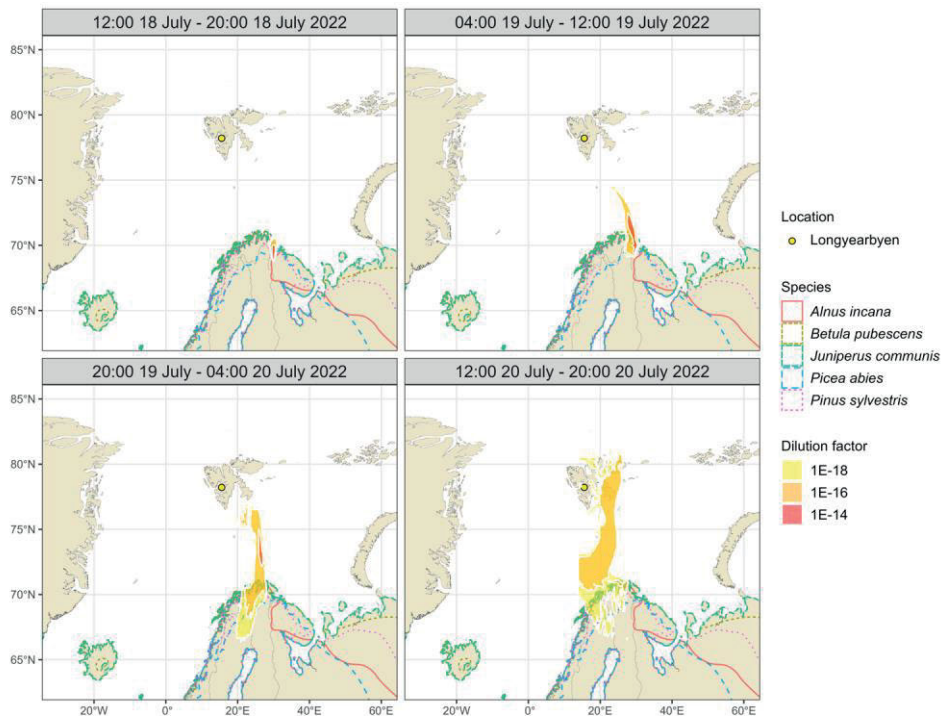


Fig. 7. Particle dispersion modelling (calculated by HYSPLIT model) showing the movement of particle plume (settling velocity = 0.012 cm s^{-1}) from potential source of pollen in North Scandinavia (start date: 18 July 2022, time:12:00).

Invertebrates. — In the pitfall water traps, we found representatives of micro- and mesofauna: Acari, Collembola, Tardigrada, and Rotifera (Table 1). The most abundant were mites (25 specimens; Fig. 8), followed by Collembola (13 specimens), Tardigrada (3 specimens) and Rotifera (a single specimen). We did not find invertebrates on sticky traps. The most taxon-rich site was Platåfjellet. Mites were found in Platåfjellet and glacier valley, rotifers and tardigrades on Platåfjellet, while collembolans on the glacier moraine only. In the traps, we found macroscopic, flying insects dominated by dipterans, which

Table 1.

List of invertebrates found in pitfall traps located above the ground in the area of Longyearbyen. Numbers of specimens are in brackets. Abbreviations: P – Platåfjellet, G – Longyearbreen Glacier, V – Valley.

Locality	P	G	V	Remarks
TARDIGRADA				
<i>Mesobiotus cf. harmsworthi</i> (Murray, 1907) (1)	+			Originally described from Svalbard (Kaczmarek <i>et al.</i> 2018). Common across Arctic tundra ecosystems (Zawierucha <i>et al.</i> 2016). Proper identification of the species requires eggs.
Unidentified (2)	+			
ROTIFERA				
Bdelloidea (1)	+			
ACARI				
Oribatida				
<i>Camisia (Camisia) ?horrida</i> (Hermann, 1804) (1)	+			Previously reported from Svalbard. Semi-cosmopolitan species.
Undetermined juveniles (2)	+			
Endeostigmata				
<i>Nanorchestes cf. antarcticus</i> Strandmann, 1963 sensu Uusitalo (2010)* (1)			+	New to fauna of Svalbard. Previously reported from Italy, Russia, and Poland (Uusitalo 2010; Laniecki <i>et al.</i> 2021).
Prostigmata				
<i>Cyta latirostris</i> (Hermann, 1804) (3)	+			Previously reported from Svalbard. Cosmopolitan species (Seniczak <i>et al.</i> 2020).
<i>Thoria brevisensilla</i> Zacharda, 1980* (2)			+	New to fauna of Svalbard. Previously reported from Czech Republic and Poland (Zacharda 1980; Laniecki <i>et al.</i> 2021).
<i>Eupodes</i> sp. (4)	+			Until now only <i>E. variegatus</i> C.L. Koch, 1838 was recorded from Svalbard (Thor 1930, 1934b), but its identity remains uncertain. The genus requires major revision.
<i>Neoprotereunetes</i> aff. <i>boernerii</i> (Thor, 1934) (1)	+			Resembles <i>N. boernerii</i> , until now reported from Svalbard and Alaska (Thor 1934a; Strandmann 1971).
<i>Bryobia</i> sp. (2)	+		+	Differ by morphology from other <i>Bryobia</i> reported from Svalbard hitherto, according to the key of Pritchard and Keifer (1958).
Trombiculidae (unidentified larva) (1)	+			
COLLEMBOLA				
<i>Agrenia bidenticulata</i> (Tullberg, 1876) (12)			+	Previously reported from Svalbard. Common in tundra and glacier adjacent ecosystems (Zmudczyńska <i>et al.</i> 2015; Gwiazdowicz <i>et al.</i> 2020).
Unidentified juvenile (1)			+	

* new to Svalbard.

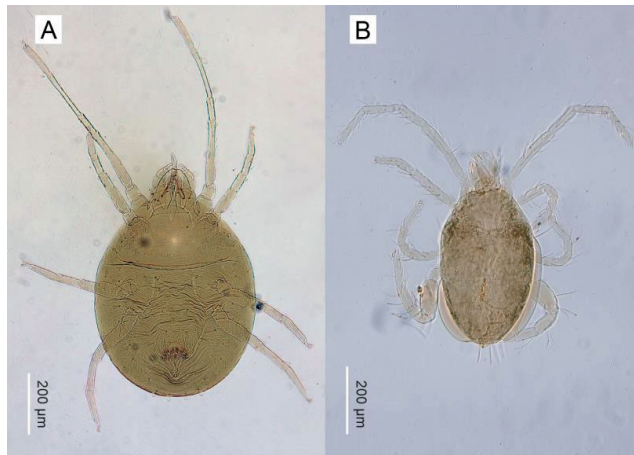


Fig. 8. Representatives of mites: (A) *Bryobia* sp. from Plateau and Valley, and (B) *Eupodes* sp. from Plateau.

likely flew into the funnels located 30 cm above the ground level. Therefore, we excluded them from our analysis and did not consider as passively transported in the wind.

Discussion

In this study, we used short-term, spatial approach to the identification of aeroplankton, that is, pollen grains and invertebrates, in central Spitsbergen. Aeroplankton over Svalbard originate from both local sources and LRT and was detected in all sampling sites (Fig. 9). We found both alien and native pollen. Invertebrates included the dominant terrestrial micro- and mesofauna in Svalbard (Acari, Collembola, Rotifera, and Tardigrada), excluding Nematoda (Fig. 9). According to our expectations, the most abundant and taxa-rich site was Platåfjellet with open landscape, strong wind gusts, variety of cryptogams, and sparse vascular plant cover.

Pollen. — Most of the pollen (68%) isolated from pollen traps belonged to non-native pollen, suggesting the influence of the long-range transport (LRT) phenomenon. The alien pollen originates from five tree taxa (*Pinus sylvestris*-type pollen, *Picea abies*, *Betula* sp., *Alnus* sp. and *Juniperus communis*) and one weed (*Urtica* sp.). Birch pollen was considered alien, as only scattered *B. nana* L. populations are found in Svalbard (Alsos and Engelskjøn 2002). All the listed plants have wide distribution range, with the northernmost populations located in Northern Scandinavia (Arnborg 1990; Enescu *et al.* 2016; Houston Durrant *et al.* 2016). Based on backward air mass trajectories analysis and particles dispersion modelling, it can be concluded that this area was the source of alien pollen recorded in the area of Longyearbyen. Windborne pollen grains are small, except

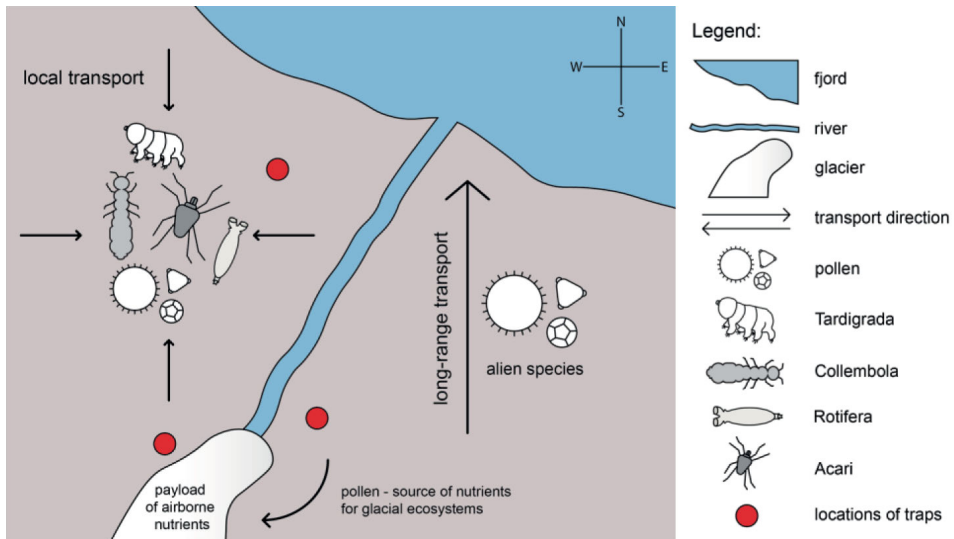


Fig. 9. Scheme presenting study area with aeroplankton transported by LRT and local transport. Aeroplankton, both pollen and invertebrates, were found in all sampling sites.

for Pinaceae pollen, which have special two air sacs acting as “balloons”, light, and dry; hence they can be easily uplifted to upper troposphere where they remain suspended by many hours (Niklas 1985).

Longyearbyen is located approximately 1000 km from the nearest tree populations of Northern Scandinavia. The LRT episodes extending over hundreds of kilometres were previously reported for such pollen types as *Betula* sp. (Skjøth *et al.* 2007; Bogawski *et al.* 2019), *Alnus* sp. (Picornell *et al.* 2020), *Pinus sylvestris*-type pollen and *Picea* sp. (Szczepanek *et al.* 2017). The LRT transport of pollen to Svalbard, Greenland and Northern Canada have also been previously described (Johansen and Hafsten 1988; Campbell *et al.* 1999; Rousseau *et al.* 2003, 2006, 2008; Jędryczka *et al.* 2022), suggesting that this could be a common phenomenon. For instance, Rousseau *et al.* (2008) concluded that transport of pollen from North America to Greenland is a general pattern, occurring every spring, following the main cyclone tracks reaching Greenland.

During our short-term monitoring study, we have also captured pollen grains of local plants, such as *Saxifraga* sp. and *Cerastium* sp. Both of them belong to insect-pollinated plants with pollen grains poorly adapted to wind dispersion; for example, they are often sticky due to pollenkitt presence, have ornamented pollen wall and relatively large size, and are produced in lower quantities (Hu *et al.* 2008). As a result, insect-pollinated pollen grains are transported on very short distances from the source plant (Hall and Walter 2011). Strikingly, these native pollen grains were observed in Platåfjellet and moraine traps (glacier was devoid of vascular plants). In addition, relatively high amount of anemophilous *Oxyria digyna* pollen was recorded, concurring with previous studies (Johansen and

Hafsten 1988; Jędrzycka *et al.* 2022). We detected significant number of grass pollen (12% of total pollen number) in contrast to Johansen and Hafsten (1988), who did not detect grass pollen throughout the entire study period (from April to August 1986) in Ny-Ålesund. High frequency of viviparity among the local grasses in high-Arctic regions could be responsible for these surprising results (Elmqvis and Cox 1996). On the other hand, such marked differences may in fact indicate that recent changes in Svalbard, in terms of climate, land cover and herbivorous pressure, are transforming the vegetation structure in favour of grassland. For instance, it is projected that plant groups with rapid growth, *e.g.*, grasses, may have greater potential to increase their dominance than the woody species currently established in Svalbard, because the latter group features relatively slower growth rates (<https://www.npolar.no>). In addition, the impact of grazing animals, such as barnacle goose *Branta leucopsis*, which population in Svalbard has increased rapidly during last decades (Tombre *et al.* 2019), may to some degree be expected to favour grasses. For instance, grazing stimulates growth rates of some grasses resulting in increased cumulative leaf length production, and nutrients released with goose faeces may enhance grass growth rates (Cooper *et al.* 2006).

Invertebrates. — The relatively high abundance of arthropods and other minute fauna in samples located at Platåfjellet and in the valley is likely related to the presence of cryptogams in sampling sites, hosting diverse faunal communities. Also, an open type of landscape may favor dispersal by strong wind gusts (Coulson *et al.* 2014). In the traps, we found windblown parts of bryophytes which can serve as a dispersal platform for some invertebrates. Data on the migration of invertebrates in the wind over Svalbard ecosystems virtually do not exist (Hodkinson *et al.* 2001; Coulson *et al.* 2002, 2003). Although Coulson *et al.* (2003) used sticky traps in glacier forefield in Kongsfjorden in order to track the invertebrate, authors focused on the macroscopic Hymenoptera, Trichoptera, and Araneae. Therefore, our study is the first to investigate the airborne transport of microscopic invertebrates in Svalbard.

Although microscopic invertebrates, like tardigrades, could be distributed through LRT (Zawierucha *et al.* 2023), there is no sufficient evidence that the newly recorded mite species, *e.g.*, *Thoria brevisensilla* Zacharda, 1980 and *Nanorchestes cf. antarcticus* Strandtmann, 1963 *sensu* Uusitalo (2010), are alien to the Svalbard fauna (Table 1). They might have been overlooked in previous studies or assigned to other species known at that time. Due to heterogeneity of Arctic ecosystems, diverse climate, and potential ice-free refugia in the past, Arctic acarine fauna is diverse and still underestimated (Coulson *et al.* 2014; Gwiazdowicz *et al.* 2020; Seniczak *et al.* 2020). Tardigrades and rotifers are ubiquitous microfauna in ecosystems around the world, including polar regions (Coulson *et al.* 2014; Zawierucha *et al.* 2016; Devetter *et al.* 2021). They are transported in wind over short and long distances (Janić 1996). Tardigrades found in this study, *Mesobiotus cf. harmsworthi* (Murray, 1907),

are common in Svalbard archipelago, inhabiting diverse substratum (Zawierucha *et al.* 2016, 2017).

Janiec (1996) suggested that invertebrates (rotifers, tardigrades, and nematodes) traveling with wind are likely first faunal migrants in glacier forefields in maritime Antarctica. Considering our findings, microscopic micro- and mesofauna could be first, wind-blown migrants in ice free areas of Svalbard. For example, *Agrenia bidenticulata* (Tullberg, 1876) is a springtail species restricted to Holarctic colder and wetter region, common in Arctic and mountain regions (Fjellberg and Bernard 2009), and is an important early pioneer species in very young terrains of glacier foreland (Hagvar *et al.* 2020). Flø and Hågvar (2013) reported this species as part of the airborne microarthropods collected with fallout traps in areas close to a retreating glacier in South Norway. For instance, mites in the traps represented different feeding modes: algivorous, fungivorous, predatory, or even obligatory ectoparasites of mammals (Trombiculidae – chigger mites), which suggests that wind could contribute to the complexity of trophic networks in forefields and tundra, and even increase the parasitism through the passive transport of invertebrates. Indeed, wind could be a vector for different group of mites including, parasitic species (Michalska *et al.* 2010; De Azevedo *et al.* 2022).

Still, taxonomic obstacles often prevent the proper identification of invertebrates, thus preparation of a detailed list of species is impossible due to scarcity of material. For example, the cosmopolitan genus *Eupodes* (four specimens) is the richest of the family Eupodidae (over 50 described species), with many subjective synonymies impossible to verify, and perhaps even more yet unrevealed synonyms and homonyms. Thor (1930, 1934a) recorded *E. variegatus* C.L. Koch, 1838 from Svalbard, but its identity is hard to determine. Collected specimens may also belong to one of the three species described by Thor (1934b) from continental Norway; however, their descriptions do not enable any explicit identification. Thus, the identification was left at the genus-level only, until the relation between boreal *Eupodes* species can be understood.

Future implications. — Atmospheric transport of other bioaerosols, such as spores, cysts, and seeds, implies new scenarios for future colonization of different ecosystems of Svalbard. Alien species and warming are two of the important factors impacting terrestrial ecosystems in Polar regions (CAFF-PAME 2017). The successful colonization by alien plants is, in polar regions, generally lower than elsewhere in the world (Wasowicz *et al.* 2020). However, the history of moss and microfaunal colonization of the virgin volcanic island near Iceland show, that such a phenomenon has already occurred and could be common (Frederiksen *et al.* 2001; Ingimundardóttir *et al.* 2014). In addition, in Europe, Svalbard archipelago experienced significant temperature increase during the last three decades (Nordli *et al.* 2014), and indeed, Bartlett *et al.* (2021) found alien species in Svalbard archipelago colonizing both natural sites and human

settlements. The monitoring of other biological particles, such as fungal spores, is generally lacking in the Arctic (Pusz and Urbaniak 2021; Koziol *et al.* 2023). The pathogenic LRT species may have a detrimental effect on native vegetation (Brown and Hovmøller 2002), while alien species could potentially become invasive.

Conclusions

Our short-term aerobiological research has yielded important insights into aeroplankton in Arctic ecosystems. We identified pollen and micro- and mesofauna originating from both local sources and long-range transport (LRT) in contrasting Arctic habitats. Bioaerosols, such as pollen grains and invertebrates, may constitute a significant allochthonous source of organic matter for other ecosystems. For example, our discovery of pollen in glacial sites suggests that they could provide an additional nutrient source for supraglacial ecosystems. At modern glacier forefields, wind becomes the vector for the initial faunal migrants that shape soil and freshwater ecosystems, underscoring the importance of aerobiology in understanding processes in proglacial ecosystems. This is particularly relevant in Svalbard, where a substantial portion of the area is covered by melting glaciers. Comprehensive studies of airborne biodiversity across Svalbard are crucial for understanding extinction, colonization, and other ecological processes in both freshwater and terrestrial ecosystems.

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Appendix. Fig. S1. Number of pollen grains collected at three monitoring stations with respect to direction of the compass.

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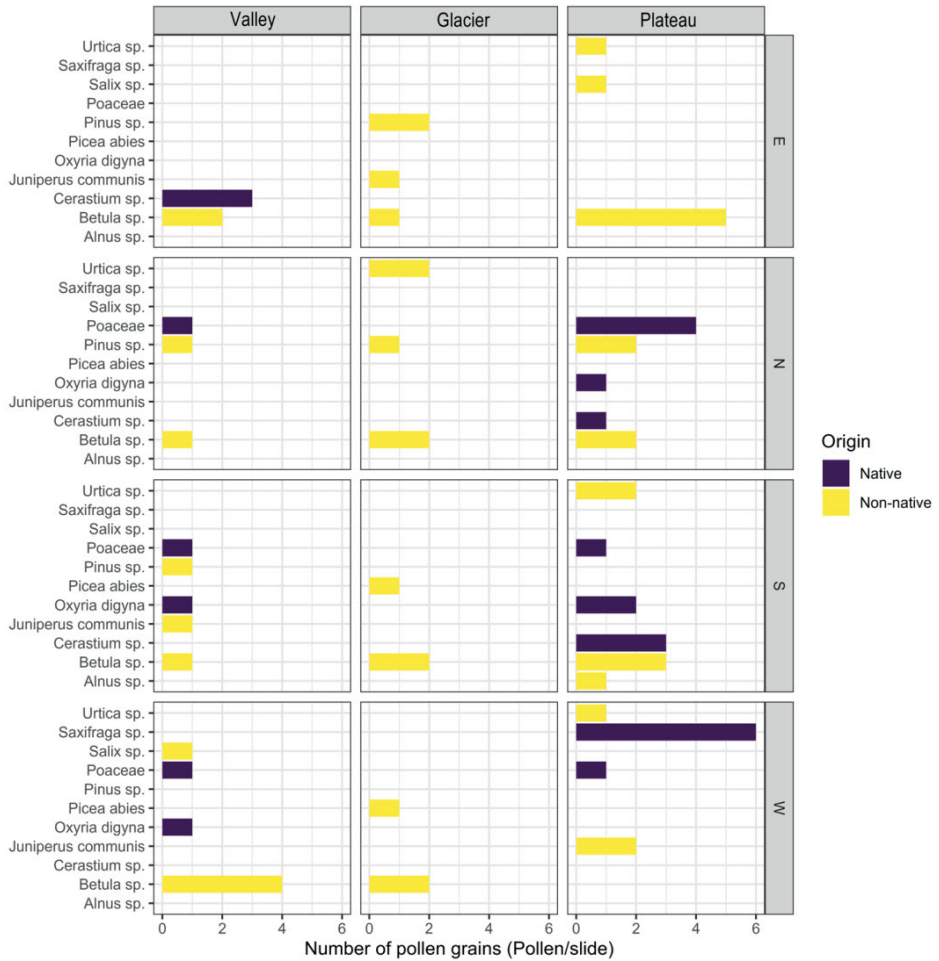


Fig. S1. Number of pollen grains in sampling sites under the different exposition (E, N, S, W).