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# Polluted fog can increase level of metal contamination in dwarf shrubs in High Arctic

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**Abstract:** The impact of pollutants on plants and their spatial distribution, whether from distant locations or local sources, is not fully understood in the High Arctic. This is particularly relevant to the accumulation of pollutants in plants growing at different altitudes. This study aims to determine the concentration of metals in the area around Longyearbyen, which is Svalbard's largest emitter of pollutants, at different altitudes. Samples of polar willow, including both shoots and roots, were collected at three sites located at altitudes of 75–461 m a.s.l. Soil samples were also collected for testing to assess the chemical composition of topsoil and the concentration of exchangeable cations and plant-available elements. We analyzed the accumulation of Cd, Cu, Mg, Mn, Fe and Zn in bark and xylem. Our research indicates that pollutant levels in plants growing at altitudes of 420–461 m a.s.l. are *ca.* 2–3 times higher than in the valley. In addition, we found that the concentration of pollutants in the bark often exceeds > 10 times the values specified for wood, especially in the case of Fe, Mn and Zn. Dendrochronological studies confirm high concentrations of pollutants at higher altitudes. Growth-ring width at polluted sites was reduced by nearly half compared to the less polluted valley plants. Plants at an altitude of > 420 meters are more frequently exposed to fog and low clouds, which directly supply them with polluted water.

**Keywords:** Arctic, Spitsbergen, metals, wet deposition, *Salix polaris*, dendrochronology.

## Introduction

The High Arctic is among the most remote regions on Earth, yet it is increasingly affected by contaminants transported from lower latitudes via atmospheric and hydrologic pathways (Headley 1996; Bard 1999; Simões and Zagorodnov 2001). Long-range atmospheric transport (LRT) delivers metals such as Pb, Cd, Zn and Cu that are deposited onto snow, soils and vegetation across polar landscapes (AMAP 2015, 2021; Gworek *et al.* 2020). Increasing seasonal access has intensified human pressures, underscoring the need for sensitive, site-specific bioindicators (Anisimov *et al.* 2007; Afflerbach *et al.* 2017; Huntington *et al.* 2023). Most atmospheric pollution in the High Arctic originates from lower latitudes. These include volcanic emissions from Kamchatka, Alaska and Iceland, the mining and metallurgical industry on the Kola Peninsula and in the area of Norilsk (in eastern Siberia) and emissions from the oil industry and shipping (Law and Stohl 2007). Atmospheric circulation, which is controlled by conditions over the Norwegian Sea, Fennoscandia and Siberia, transports these pollutants towards the central parts of the Arctic Sea (Law and Stohl 2007; Stock *et al.* 2014; Nawrot *et al.* 2016). Depending on how pollutants are transferred to the environment, deposition can be classified as dry, wet, or fog. Direct deposition of fog to ve-

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getation is particularly efficient in low clouds with bases below the level of plateaus and ridges (Myśkow *et al.* 2019).

Svalbard, especially the vicinity of Longyearbyen, exemplifies the combined influence of LRT and local sources (Zaborska *et al.* 2017; Rudnicka-Kępa and Zaborska 2021). Winter circulation frequently advects anthropogenic pollution from Europe and Russia, elevating aerosol and trace-element loads over the archipelago (Drbal *et al.* 1992; Birks *et al.* 2004). Superimposed on this background are emissions from energy production, vehicular traffic, a century of coal mining, and resuspension of coal-rich dust, producing spatially heterogeneous contamination around the settlement (Jóźwik 2000). After deposition, metals may be re-emitted, immobilized in soils or assimilated by plants. Approximately 90% of terrestrial Hg is sequestered by vegetation, whereas Cd and Pb are taken up mainly through roots, with foliar interception important near sources (Ismael *et al.* 2019; Schaefer *et al.* 2020; Zhou *et al.* 2021). Cryptogams (mosses, lichens) efficiently intercept atmospheric metals and are widely used as bioindicators (Grodzińska and Godzik 1991; Bargagli 2016; Wojtuń *et al.* 2018; Dziurowicz *et al.* 2025). Around Longyearbyen, elevated Pb, Cd, Cu and Zn in cryptogams and surface soils generally decline with distance and elevation from sources (Łokas *et al.* 2019), but such surveys reveal little about root-mediated uptake or longer-term internal storage in vascular plants (Saarela *et al.* 2005; Cocozza *et al.* 2016; Martin *et al.* 2018).

Tree-based studies clarify how different tissues register pollution: wood and growth rings can reflect the temporal evolution of heavy-metal availability, while bark directly receives atmospheric deposition on its outer surface (Sawidis *et al.* 2011; Chiarantini *et al.* 2016; Martin *et al.* 2018). The precise pathways into annual rings remain debated, and reconstructing histories from bark is complex (Rodríguez Martín *et al.* 2014; Chiarantini *et al.* 2016). Nonetheless, organ-resolved analyses, including paired bark/wood, help separate depositional from internal signals (Saarela *et al.* 2005). These lessons motivate a shrub-based approach for Svalbard. *Salix polaris* Wahlenb., a common and abundant plant around Longyearbyen, bridges soil and atmosphere; bark is a near-surface interface sensitive to recent deposition, whereas xylem wood integrates medium- to long-term internal accumulation and translocation, enabling a tissue-resolved view of exposure pathways in a treeless landscape (Martin *et al.* 2017; Myers-Smith *et al.* 2020; Owczarek *et al.* 2021).

Local context further supports this focus. Longyearbyen, having *ca.* 2200 residents, has a coal/diesel power plant, intense seasonal transportation, and a long coal mining legacy, as well as extensive abandoned infrastructure. Weathering and thaw of waste-rock piles and mine areas generate leachates and acid mine drainage, while windborne coal particles disperse broadly signals that are detected in soils, snow and aerosols near infrastructure (Cecinato *et al.* 2000; Rodríguez Martín *et al.* 2014; Weinbruch *et al.* 2015; Chiarantini *et al.* 2016; Gallet *et al.* 2019). Moreover, the altitudinal variation modulates exposure by affecting snow distribution, soil moisture, permafrost dynamics and vegetation structure. Although metals in cryptogams and soils generally decline with elevation and distance from sources, it remains unclear whether similar gradients occur in *S. polaris* tissues across Longyearbyen's topography (Łokas *et al.* 2019).

Accordingly, we quantify Cd, Zn, Cu, Fe, Mg and Mn in the bark and xylem wood of *S. polaris* from three altitudinal sites around Longyearbyen. For the first time in the Arctic, we investigate the relationship between pollutants accumulated in plants growing in a vertical gradient and dendrochronological data. Our main objectives are to (*i*) resolve spatial trends in tissue metal loads across sites, (*ii*) contrast bark, as the interface with recent deposition, with wood, as an integrator of medium- to long-term internal accumulation, and (*iii*) assess the impact of altitude on the distribution of pollution, especially the impact of polluted fog.

## Study area

The study was carried out in the central part of Spitsbergen, the largest island in the High Arctic Svalbard archipelago (Fig. 1A). The landscape of this part of Spitsbergen is mainly characterized by wide plateau at an elevation 420–550 m a.s.l., above which single peaks and mountains rise to up to 1050 m a.s.l. (Fig. 1B). This type of relief is closely related to the geological structure, which consists of near-horizontal layers of sandstones, siltstones, and shales from the lower Cretaceous and lower Tertiary (Hjelle 1993). The elevated plateaus are often covered by rock debris with frost-patterned ground (Fig. 1B). In contrast, more profound erosional processes give rise to U-shaped valleys with extensive braided river systems and alluvial cones (Fig. 1C). There are small glaciers in the upper parts of the valleys and cirques, which have been rapidly retreating since the late 20$^{th}$ century (Małecki 2016). The study area is characterized by prevalence of Turbic Cryosols and Haplic Cryosols in the river valleys, whereas Skeletic Cryosols and Turbic Cryosols are the most common soils in the mountains (Szymański *et al.* 2022a, 2022b; Bartos *et al.* 2023). The soils show loamy texture and acidic reaction as well as various content of organic matter due to heterogeneous environmental conditions such as vegetation cover, soil wetness, and microclimate (Szymański *et al.* 2022a, 2022b; Bartos *et al.* 2023, 2024).

According to Köppen's system, the climate represents the tundra polar subtype (ET), with the average annual air temperature of –4.5°C and seasonal air temperatures varying between 11.7°C in winter and 5.2°C in summer. Compared to other parts of Spitsbergen, this area receives very low annual precipitation of 207.9 mm. Within plateaus, the dominant vegetation type is tundra classified as cryptogam, herb barren. This habitat is characterized by dry to wet barren landscapes with very sparse, extremely low-growing plant cover. Prostrate shrubs < 5 cm

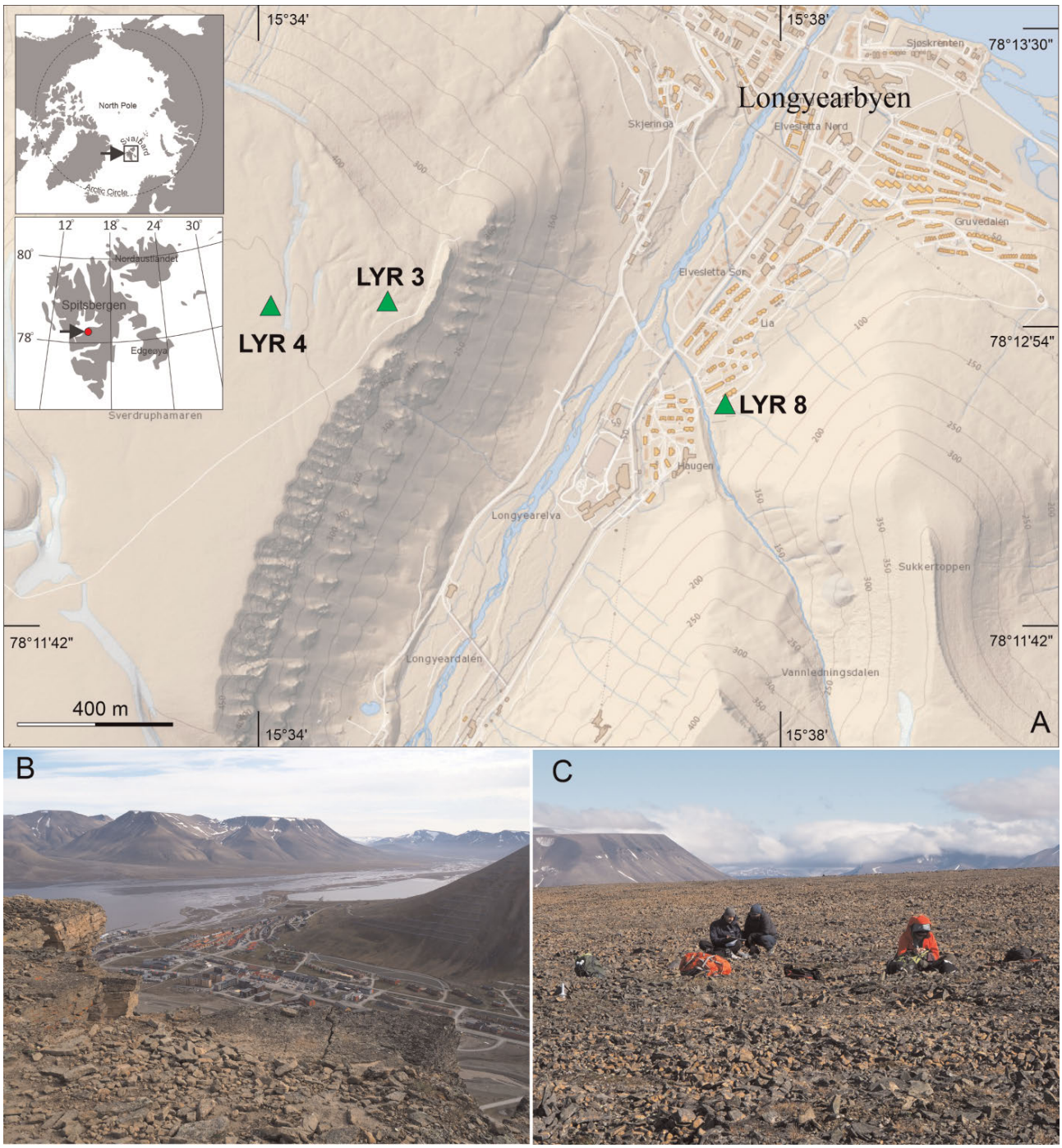


**Fig. 1.** (**A**) Locations of the research sites in the close vicinity of Longyearbyen in the central part of Spitsbergen, (**B**) general view of Longyearbyen and the lower part of the Longyerelva Valley with location of the LYR 8 site, (**C**) general view of Platåberget covered by loose rock material, where the LYR 3 and LYR 4 research sites were located.

tall, such as *Dryas octopetala* and *Salix polaris*, along with graminoids and forbs, dominate in lower elevations and valleys.

The research sites are located near Longyearbyen (Fig. 1A), which is the largest settlement in Svalbard. Although its pollution level is generally low, it has numerous pollution sources. These are a coal and diesel fuel power plant and transportation, *e.g.*, snowmobiles, passenger cars, heavy-duty vehicles, vessels, and aeroplanes. Coal mining in the Longyearbyen area began in 1906, and seven mines were established. Although the last one was closed on 30 June 2025, the remains of the mines and industrial waste dumps accumulated over decades still exist and continue to have a negative impact on the environment (Askaer *et al.* 2008). To determine the impact of altitude on the accumulation of pollutants in plants, sites located on a plateau at an altitude of > 400 m a.s.l. (LYR 3: 420 m a.s.l., LYR 4: 461 m a.sl.) (Fig. 1B) and site located in the valley, in proximity to the settlement (LYR 8: 75 m a.s.l.) (Fig. 1C), were selected.

## Materials and Methods

### Plant material, sampling and analysis

For each study site established at the *Salix polaris* sampling locations, vegetation communities were characterized using phytosociological relevés, each covering an area of 100 m². Relevé locations were selected following the cardinal principle of identifying uniform and homogeneous plant community surfaces, as described by Braun-Blanquet (1964). *Salix polaris* (Wahlenb.), known as Polar willow, is widespread in the Svalbard archipelago, notably within south-western Spitsbergen and Edgeøya (Elvebakk 1994, 1997; Rønning 1996). Its prevalent distribution across Spitsbergen makes it a bioindicator species of environmental change, both natural and anthropogenic (Buchwal *et al.* 2013; Owczarek *et al.* 2013, 2014 Opala-Owczarek *et al.* 2018; Wojtuń *et al.* 2019). *Salix polaris* has a dense network of roots and woody shoots, although dark green leaves are usually visible on the surface (Fig. 2A). The woody part of the plant, where measurable annual growth rings with clear boundaries are visible, is surrounded by thick bark that protects it from extreme environmental conditions (Fig. 2B).

Samples of *S. polaris* were collected during two field campaigns, 2022 and 2023, from three sites: one at a low elevation in Longyeardalen Valley (LYR 8), and two on the Platåberget (Sverdruphamaren) plateau at an elevation of 420–461 m a.s.l. (LYR 3 and LYR 4). At every site, we randomly collected 15–20 individuals, depending on the availability in a given location. The specimens were analyzed in the laboratory in two ways: dendrochronologically, to determine the characteristics of plant growth, and for metal content. For dendrochronological analysis, we adapted well-established microscopic techniques for dwarf shrubs (Gärtner and Schweingruber 2013). We carefully selected undamaged sections from each plant's main root and shoots. These samples were then rehydrated and thinly sliced to a 15–20 µm thickness, using a GSL 1 sledge microtome (Gärtner *et al.* 2014). Serial sectioning (Kolishchuk 1990; Myers-Smith *et al.* 2015) allowed for a detailed examination across various parts of each plant, addressing any absent or compressed rings. To measure growth rings, we captured digital photographs of each micro-section under 10x magnification, or 20x magnification for less regular samples. Given the prevalence of wedging and partially missing rings related to eccentric growth, at least two radii were measured under visual control using the WinDENDRO tree-ring system (Rinn 2003), ensuring accuracy in our analysis of growth-ring variability. We conducted cross-dating in three stages: first, among all measurements within each cross-section; next, among all measurements within each plant; and final, across the results from every site. The constructed chronologies were statistically verified in the program COFECHA (Grissino-Mayer 2001). Following this, the TRW series were standardized with the ARSTAN software (Cook and Holmes 1996) using a straight line with a horizontal slope, as no distinct age trend was revealed in the analyzed specimens.

Wood and bark samples of *S. polaris* were separated and washed prior to drying, packed into paper envelopes, and dried at 70°C for three days in a drier (WGLL-65BE, ChemLand, Poland). After drying, the samples were weighed using the same analytical balance. The dry wood and bark material was ground in a mortar, homogenized, and acid-digested in a microwave-assisted wet digestion system (ETHOS1, Milestone, Italy). The digestion protocol was developed for this study, taking into account the longer mineralization time required for woody tissue compared with typical herbaceous plant material, and used concentrated $HNO_3$ (65%, suprapure grade; Carlo Erba, Italy) and $H_2O_2$ (30%; Stanlab, Poland) in a 4:1 (v/v) ratio. Metal concentrations in the digests were determined

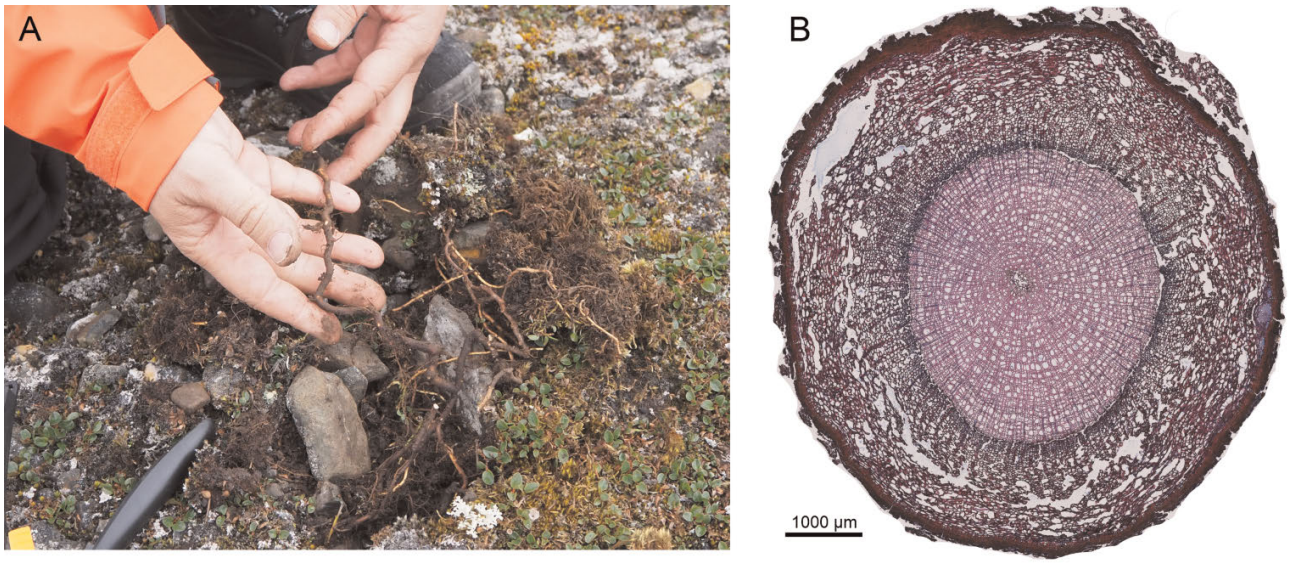


**Fig. 2.** An example of *Salix polaris* collected for laboratory analysis (**A**), note the long, thick main root and the dense network of thin, woody shoots and (**B**) cross-section through a woody shoot of *Salix polaris*; thick bark accounts for almost 50% of the entire cross-section.

by flame atomic absorption spectrophotometry (iCE 3500 FAAS; Thermo Scientific, USA). Reference plant material (Oriental Basma Tobacco Leaves [INCT-OBTL-5]; Institute of Nuclear Chemistry and Technology) was used to ensure analytical quality control. The results are shown as the means ± SE. To enable comparison of the significance of differences between examined *Salix polaris* populations in element concentration, a one-way ANOVA and a post hoc Fisher LSD test was used ($p < 0.05$). The statistical analysis was performed using Statistica v.13.1 software (Dell Inc., Austin, TX, USA).

### Soil sampling and analysis

Soil samples were collected from the 0–10 cm surface layer to plastic bags and transported to the laboratory. In the laboratory, the samples were air dried at 22°C, gently crushed, and passed through a 2 mm stainless steel sieve. All living roots were removed from the soil samples. All soil analyses were performed using a fine-earth material, *i.e.*, fraction < 2 mm. Particle-size distribution was determined using a hydrometer method (silt and clay fractions) and sieving (sand fraction) according to Gee and Bauder (1986). Soil pH was measured potentiometrically in deionized water (1:2.5 w/v ratio) using a glass electrode (Thomas 1996). Content of total carbon (TC) and total nitrogen (TN) was determined in triplicate and then averaged, using a Vario Micro Cube CHN elemental analyzer (Vario Micro Cube, Elementar, Hanau, Germany). The content of TC was assumed as soil organic carbon content (SOC) due to the fact that all studied soil samples did not contain carbonates. The chemical composition of fine earth material (< 2 mm) was determined using Inductively Coupled Plasma-Emission Spectrometry (ICP-ES) at a certified laboratory of Bureau Veritas (Vancouver, BC, Canada). Concentration of exchangeable alkaline cations ($Ca^{2+}$, $Mg^{2+}$, $K^{+}$ and $Na^{+}$) was measured using Flame Atomic Absorption Spectrometry (FAAS) after extraction with 1M ammonium acetate at pH = 7 (Sumner and Miller 1996). Concentration of exchangeable acidic cations $H^{+}$ and $Al^{3+}$ extracted using 1M KCl was determined by titration of extracts, after boiling for 10 s, with 0.1 M NaOH in the presence of phenolphthalein (Summer 1992). The colorimetric method (Kuo 1996) and FAAS were used to determine concentration of plant available phosphorus (Pav) and potassium (Kav), respectively. Concentration of plant available magnesium (Mgav) was measured by FAAS after extraction procedure according to Schachtschabel (1954). Determination of exchangeable alkaline ($Ca^{2+}$, $Mg^{2+}$, $K^{+}$, and $Na^{+}$) and acidic ($H^{+}$ and $Al^{3+}$) cations as well as plant available elements (Pav, Kav, Mgav) concentration was done in certified laboratory of Bureau of Forest Management and Geodesy in Kraków.

Quality control for ICP-OES was ensured by the certified laboratory's internal protocols (ISO 17025 compliant). For FAAS (iCE 3500, Thermo Scientific), the limits of quantification (LOQ) were established based on 10 times the standard deviation of blank measurements. The precision of the method was monitored by analyzing samples in triplicate, with relative standard deviations (RSD) consistently < 5%. Linearity was maintained by keeping the absorbance values within the 0.05–0.5 range.

## Results

### Vegetation characteristics

To properly assess the variability in contaminant levels, we had to conduct a detailed analysis of the plant communities. The research sites are located in phytosociologically diverse areas, including a flat, rocky plateau Platåberget (LYR 3 and LYR 4), and the lower part of the slope of Gruvefjellet in the Longyeardalen valley (LYR 8). Platåberget is characterised by > 80% cryptogam dominance, with *Umbilicaria hyperborea, Rhizocarpon geographicum, Lecanora polytropa* and *Pseudephebe pubescens* forming continuous crusts or mats. Vascular plants, like *Salix polaris*, appear only as scattered stress-tolerant individuals. Such composition corresponds with descriptions of cryptogam-dominated polar desert terrains across Svalbard and other High Arctic archipelagos, where extreme abiotic stress results in vegetation physiognomy governed almost entirely by lichens and bryophytes (Rønning 1996; Węgrzyn and Wietrzyk 2015). The association develops on steep, wind-exposed slopes, blockfields and frost-shattered ridges, where soil formation is nearly absent. These features correspond directly to the polar desert ecotone described for the highest and driest surfaces of the central Spitsbergen landscape, which represents extremely poorly developed High Arctic fellfield vegetation (Elvebakk 2005). The lower parts of the slopes in the valley area, in contrast, have significantly greater biodiversity. This community is characterised by the co-dominance of evergreen dwarf shrubs (*Cassiope tetragona*), hemiprostrate shrubs (*Dryas octopetala*, *Salix polaris*), and a dense field layer of arctic herbs and graminoids. The presence of a continuous soil layer enables higher productivity and greater vegetation height compared to fellfields. Bryophytes and lichens remain abundant but clearly subordinate. These floristic and structural features reflect classic mesic tundra ecosystems on Svalbard with moderate moisture and improved nutrient cycling (Elvebakk and Prestrud 1996; Walker *et al.* 2005). The floristic composition of the sites within the valley is typical of stable, moist slopes and mesic tundra patches in the Longyearbyen area. It corresponds to the well-known shift from cryptogam-dominated to vascular-dominated vegetation under improved soil and moisture conditions (Węgrzyn and Wietrzyk 2015). Based on research by Wojtuń *et al.* (2019), vegetation in the valley floor near Longyearbyen is a bioindicator of trace element pollution. Increased metal content was found in *Sanionia uncinata* and *Salix polaris*, and it was pointed to as local contamination sources, such as exhaust from power plants, traffic, coal mines, and industrial waste dumps. However, for comparison purposes, samples from upland areas were not analysed.

### Variation in metal content in plants *vs.* growth response

Analyses of metal concentrations revealed significant variations depending on the location of the site and the type of material being investigated (Fig. 3). In the wood of *S. polaris*, concentrations of the macronutrient Mg were consistently higher than those of the micronutrients Fe, Mn, and Zn at all tested fields and in both shoots and roots. Across sites LYR 3, LYR 4, and LYR 8, Mg ranged from *ca.* 530 to 3330 µg g DW. A translocation factor > 1 was observed only for site LYR 4. For the remaining sites, Mg accumulation in shoots was significantly lower than in root wood. In the case of Cd, Mn, and Zn, no significant differences were found between the accumulation in the wood of willow shoots and roots from sites LYR 3 and LYR 4. However, the highest Cd content was found in the wood of *S. polaris* shoots from LYR 3 among all the wood samples tested. The shoot wood from LYR 8 was characterized by the lowest accumulation of Cd, Cu, Mg, Mn, and Zn, and at the same time, it had the significantly highest Fe content among the studied populations. The translocation factor coefficient for Fe in the shoot wood of willows from LYR 8 was also higher than 1.

In bark, absolute concentrations of Cd, Fe, Mg, Mn, and Zn were markedly higher than in wood, especially for Fe. Statistically, the highest amount of Fe was found in the shoot bark of the LYR 4 population, while the lowest amount was found in the root bark of the LYR 3 and LYR 8 populations. For Cd and Cu, changes in the content of elements in the bark of shoots and roots corresponded to the relationships observed in wood. For Mg, no significant differences in accumulation were measured between sites or plant organs. The highest Mn accumulation was recorded in the root bark of the LYR 4 population, while the lowest values were measured in the bark of the LYR 8 population. The highest copper concentrations were detected in the root bark of LYR 4, similar to the accumulation of this metal in wood. We demonstrated increased accumulation of heavy metals (Cd, Zn), but also Mn, in the tissues of *S. polaris* growing at higher elevations compared to valley sites. We measured significantly higher concentrations of all investigated metals in *S. polaris* bark than in wood (Fig. 3). At low elevation, we detected maximum Cd content in *S. polaris* shoot at 4.7 ppm, whereas at an altitude of 400 m above valley bottom this value was as high as 13 ppm (Fig. 3). The same was the case for Zn, when in the higher-located populations the metal accumulation reached a record 1200 ppm, while in the valley the maximum values did not exceed 600 ppm (Fig. 3).

The question arises as to whether pollution can affect the width of annual growth rings of *S. polaris*? As a result of dendrochronological research, two chronologies of annual growth widths were compiled, covering the years 1988–2022 for LYR 3 and LYR 4 sites and 1992–2022 for LYR 8 site. The width of annual increments in high and low elevation sites is characterised by very high variability, which is typical for *S. polaris* (Fig. 4). Although certain sections of dendrochronological scales show similarities in their course, like the rain-on-snow event in 2014, there is nevertheless a noticeable heterogeneity in their patterns (Fig. 4). Narrower rings were found at higher altitudes (mean growth ring width: 64 µm) than at lower ones (mean growth ring width: 102.4 µm) (Fig. 4). The most important factor influencing this trend appears to be altitude and harsher growing conditions. Conversely, although the growing season is longer at lower altitudes, drought stress occurs in the second half of the season. Therefore, wider growth rings may primarily be the result of a higher content of exchangeable cations and elements available to plants in the topsoil. Taking this into account, it can be assumed that in higher locations, in addition to climatic conditions, high concentrations of pollutants will also contribute to a reduction in the width of the growth rings.

### Soil characteristics

The studied topsoils were characterized by acidic (sites: LYR 3 and LYR 4) and slightly acidic reaction (site LYR 8), due to lack of carbonates in the parent material. The topsoils occurring in mountain area showed lower content of SOC and TN as well as C/N ratio in comparison with the topsoil from the Longyeardalen valley (Table 1). Chemical composition of all the topsoils was similar (Table 1); however, topsoils occurring in the mountains (sites: LYR 3 and LYR 4) contained higher amount of $SiO_2$, and slightly lower amount of $Al_2O_3$, $Fe_2O_3$, MgO, CaO, $Na_2O$, and $K_2O$ than topsoil from the Longyeardalen valley (site LYR 8). The chemical composition of the topsoils is associated with highly siliceous parent material (Table 1), *i.e.*, residues of sandstones and siltstones, which prevail in this area (Dallmann *et al.* 2001; Szymański *et al.* 2019). The topsoil from the Longyeardalen valley showed clearly higher concentration of $Ca^{2+}$ and slightly higher concentration of $Mg^{2+}$ as well as lower concentration of $H^+$ and $Al^{3+}$ than the topsoils from mountains and this is main reason of slightly higher pH of the topsoil from the valley. In addition, concentrations of plant available potassium and magnesium were higher in the topsoil from the valley than from the mountains (Table 1). All the topsoils showed loamy texture, *i.e.*, loam or sandy loam (Table 1), because weathering of clastic rocks such as sandstone, siltstone and shale leads to formation of residues and deposits showing loamy texture. However, topsoils from mountains were characterized by higher content of sand fraction and lower content of silt fraction than topsoil from the valley, which is most likely related to local heterogeneity of residues as well as wind activity.

### Principal component analysis

The selected variables explained nearly 88% of the total variance, which supports the identification of significant regularities in this analysis (Fig. 5). Principal component analysis confirmed the importance of soil pH and SOC in differentiating populations and in metal accumulation. *Salix polaris* populations clustered along an elevation gradi-

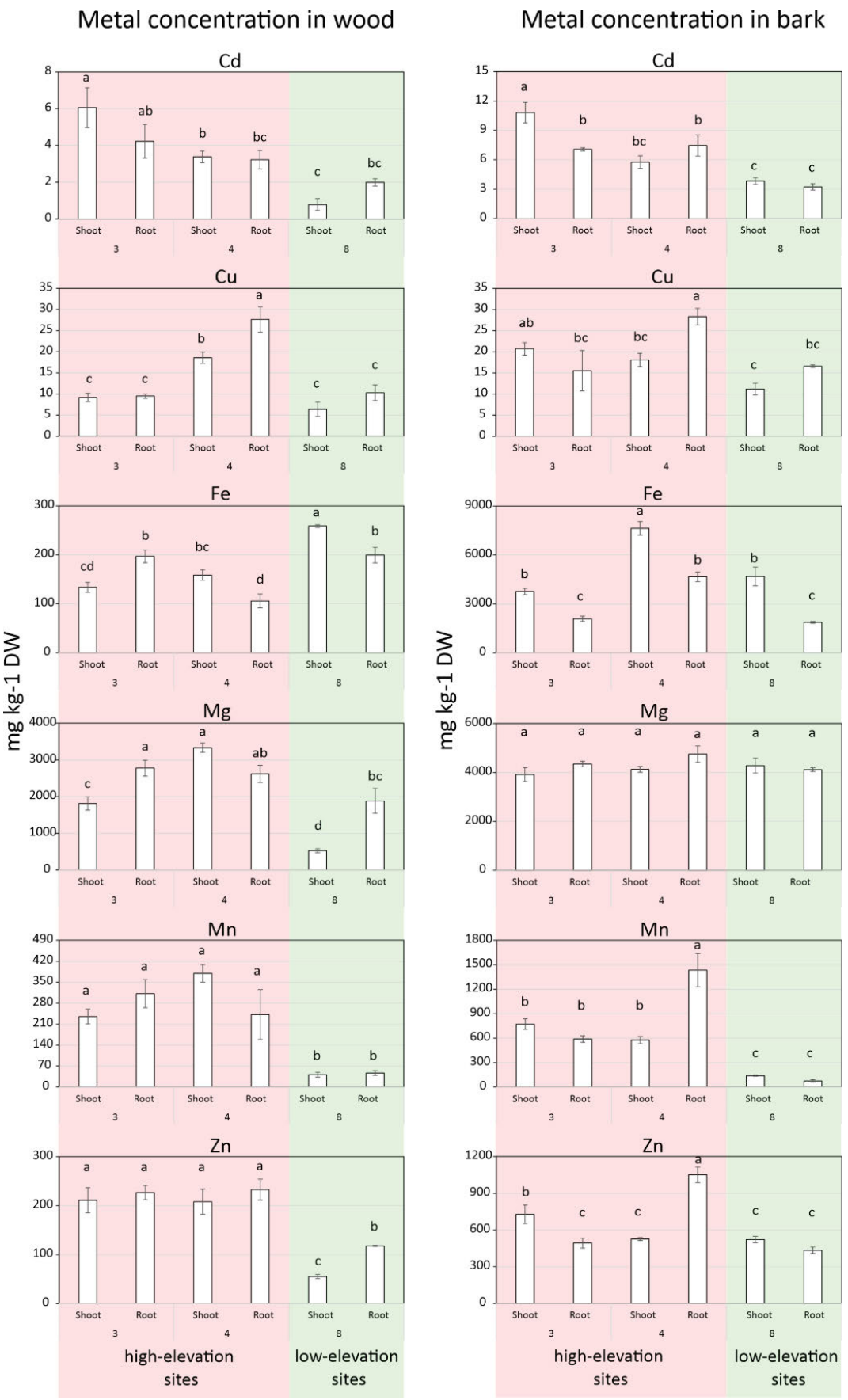


**Fig. 3.** Metal concentration in wood and bark of wooden shoots and roots in high-elevation research sites LYR 3 and LYR 4 and in low-elevation site LYR 8. Presented data are means ± SE (n = 3). Means followed by the same letter for each metal concentration in *Salix polaris* tissue are not significantly different from each other using the LSD test ($P < 0.05$).

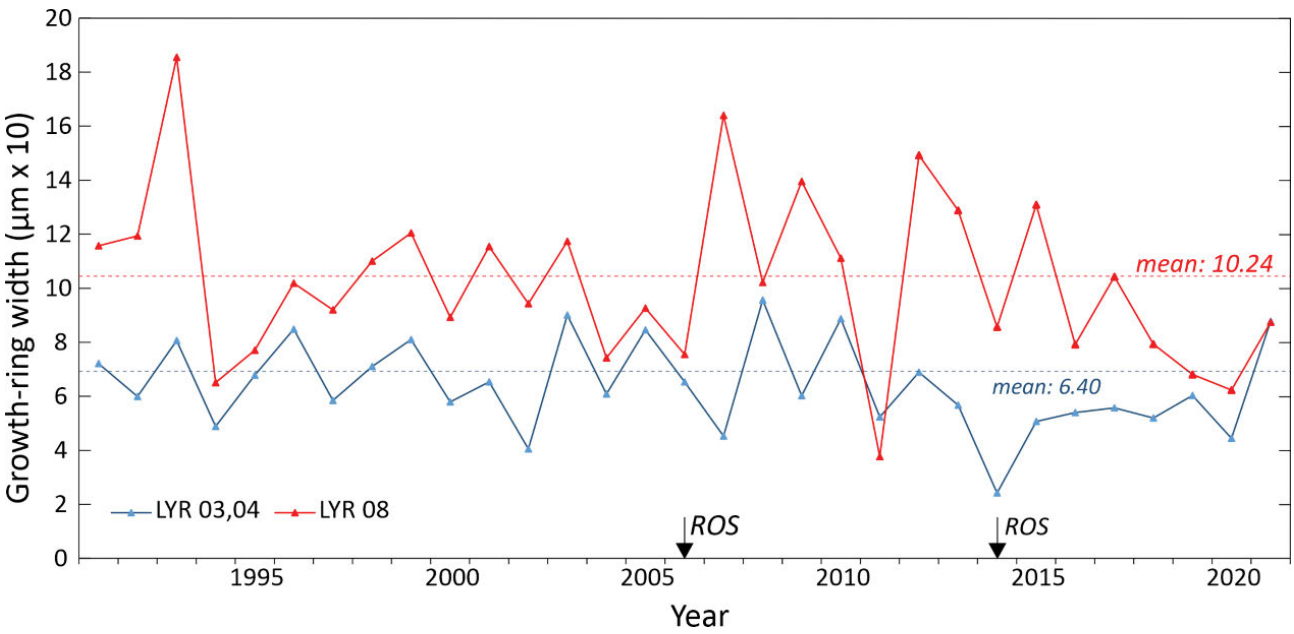


**Fig. 4.** Growth-ring chronology of *Salix polaris* growing at high (blue line) and low (red line) elevation sites with marked average width of annual increments and rain-on-snow (ROS) events.

ent, as did heavy metal contamination, supporting the fog deposition hypothesis. The analysis also confirmed a negative correlation between annual wood growth and elevation above the valley floor. The analysis also showed that Zn content in *S. polaris* bark was nonspecific, unlike the accumulation of this metal in wood.

## Discussion

### Metal content in the plants

Heavy metals are important environmental pollutants that can affect Svalbard's ecosystems, as well as those across the entire Arctic, both directly and indirectly. In addition to the primary sources of pollution, such as long-range and local transport pathways, pollutants present in the terrestrial environment are also released from secondary sources, such as riverine runoff (Rudnicka-Kępa and Zaborska 2021). Although the overall influx and transport of pollutants is relatively well understood (Zaborska *et al.* 2017), little is known about their spatial distribution in relation to the topography, altitude, and their concentration in the different anatomical parts of Arctic woody plants. The metal concentrations we measured were within the physiological ranges already published for *S. polaris* (Wojtuń *et al.* 2019) and *S. arctica* (Ermakov *et al.* 2015). Significantly higher concentrations of metals in willow bark than in wood detected in all sites confirms the results obtained for other willow species (Zárubová *et al.* 2015) and for birch (Sitko *et al.* 2021). Wojtuń *et al.* (2019) measured the maximum Cd content in *S. polaris* shoots in Longyearbyen at 5.0 ppm, while our maximum for this population was 4.7 ppm. At the same time, populations located 400 m above the valley bottom reached maximum Cd accumulation of 13 ppm. The same was the case for Zn, when in the higher-located populations the metal accumulation reached a record 1200 ppm, while in the valley the maximum values were half as high, and in previous research with the maximum at 433 ppm (Wojtuń *et al.* 2019). On the one hand, our results are strongly related to the studies of our predecessors; on the other hand, they shed new light on the increase in metal accumulation in plant tissues, including toxic trace metals such as Cd and Zn, at higher-lying sites.

The annual growth rings of *S. polaris* are characterised by very high variability, which is typical for Arctic shrubs (Owczarek and Opała 2016; Le Moullec *et al*. 2019; Opała-Owczarek *et al*. 2019; Owczarek *et al*. 2021; Phulara *et al*. 2025). Wider ring widths were observed at lower altitudes. Given the adverse effects of drought stress at lower altitudes during the second half of the growing season, these higher values should be attributed to nutrient supply and better physicochemical soil conditions, *e.g.*, high concentration $Ca^{2+}$ and $Mg^{2+}$ in comparison with sites located at higher altitudes (Phulara *et al*. 2025). Higher contents of soil organic carbon, total nitrogen and the C/N ratio, compared with sites located on the plateau, indicate better soil conditions that may offset the negative impact of drought stress at lower elevations. These relationships between the physicochemical properties of the soil and the development of vegetation cover in central Spitsbergen have previously been described by Szymański *et al.* (2019) and Bartos *et al.* (2023, 2024). At higher altitudes in central Spitsbergen, no negative impact of drought stress on annual ring width was observed, as described in detail by Phulara *et al*. (2025). Consequently, the significantly narrower ring widths at higher altitudes may be due not only to the slightly poorer physicochemical properties of the topsoil, but also to the impact of environmental pollution. To date, no research has been conducted on the impact of pollution on the reduction of annual

**Table 1.** Chemical and physical properties of the studied topsoils.

| Property \ Site | LYR 3 | LYR 4 | LYR 8 |
|---|---|---|---|
| Horizon | A | AC | A |
| Depth (cm) | 0–10 | 0–10 | 0–10 |
| pH ($H_2O$) | 5.87 | 5.92 | 6.56 |
| SOC (%) | 1.63 | 0.58 | 2.65 |
| TN (%) | 0.17 | 0.07 | 0.17 |
| C/N | 10 | 8 | 15 |
| Rock fragments (%) | 60 | 40 | 30 |
| Sand (%) | 65 | 46 | 42 |
| Silt (%) | 29 | 43 | 47 |
| Clay (%) | 6 | 11 | 11 |
| Soil texture (USDA) | sandy loam | loam | loam |
| $SiO_2$ (%) | 69.75 | 75.99 | 62.51 |
| $Al_2O_3$ (%) | 11.30 | 10.11 | 14.24 |
| $Fe_2O_3$ (%) | 5.99 | 4.58 | 6.80 |
| MgO (%) | 0.73 | 0.60 | 1.06 |
| CaO (%) | 0.31 | 0.22 | 0.48 |
| $Na_2O$ (%) | 1.45 | 1.46 | 1.56 |
| $K_2O$ (%) | 2.39 | 2.19 | 2.48 |
| $TiO_2$ (%) | 0.58 | 0.59 | 0.80 |
| $P_2O_5$ (%) | 0.16 | 0.09 | 0.16 |
| MnO (%) | 0.05 | 0.05 | 0.05 |
| $Ca^{2+}$ (cmol/kg) | 3.30 | 2.32 | 7.85 |
| $Mg^{2+}$ (cmol/kg) | 1.83 | 1.22 | 2.48 |
| $K^+$ (cmol/kg) | 0.18 | 0.09 | 0.18 |
| $Na^+$ (cmol/kg) | 0.08 | 0.07 | 0.07 |
| $H^+$ (cmol/kg) | 0.13 | 0.13 | 0.09 |
| $Al^{3+}$ (cmol/kg) | 1.27 | 1.36 | 0.00 |
| $K_{av}$ (mg/100 g) | 5.52 | 2.50 | 6.14 |
| $Mg_{av}$ (mg/100 g) | 38.32 | 26.72 | 46.25 |
| $P_{av}$ (mg/100 g) | 0.06 | 1.32 | 0.38 |

growth in Arctic shrubs. Nevertheless, this concern has been thoroughly researched, for example in polluted areas of the Russian subarctic (Nöjd and Reams 1996; Kirdyanov *et al.* 2014; Kharuk *et al.* 2023) and in the mountains of Central Europe (Opala-Owczarek *et al.* 2018; Myśkow *et al.* 2019). In the case of long-term increment series obtained from trees growing in areas subject to strong pollution pressure, reductions in increment width for the period of highest contamination and a change or weakening of the dendroclimatic signal are characteristic. However, the length of the *S. polaris* increment chronology is insufficient for a comparative analysis of the polluted and unpolluted sub-periods. Further research in dendroecology and dendrochemistry of Arctic tundra plants will require the inclusion of additional reference sites or the discovery of older specimens dating from times before the increase in pollution emissions to fully assess the impact of pollution on the dendrochronological record, as well as ultra-high-resolution analyses of isotopic and elemental composition in individual annual growth rings. Ring-resolved micro-analyses (*e.g.*, LA-ICP-MS, μXRF) should be used to build year-by-year metal series and directly test the fog-interception mechanism. Overall, bark captures recent inputs, xylem integrates longer-term exposure, and elevation/site

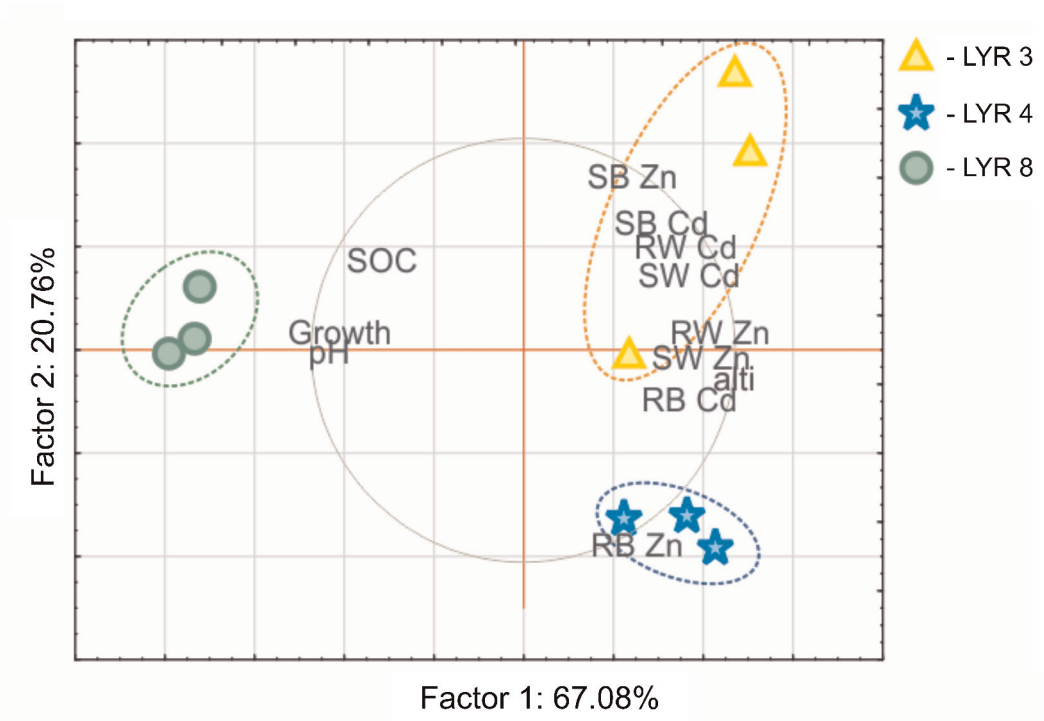


**Fig. 5.** Principal component analysis presenting the relationships between some environmental factors and heavy metal accumulation in different tissues of *Salix polaris* growing on three sites (LYR 3, LYR 4, LYR 8). Abbreviations: alti – site's altitude, pH – soil pH, SOC – soil organic carbon; Growth – growth-ring width, RB – metal accumulation in root bark, RW – metal accumulation in root wood, SB – metal accumulation in shoot bark, SW – metal accumulation in shoot wood.

context modulates both, supporting *S. polaris* as a practical indicator system for distinguishing between near-term deposition and longer-term uptake, and for tracking metal contamination in a rapidly changing High-Arctic environment. Progress in specific disciplines, analytical advances, and large-scale pan-Arctic sampling campaigns aiming at complex analysis of environmental effects on shrubs growth, will increase the research potential of shrub and dwarf shrubs growth-rings.

## Effect of fog pollution

Our research indicates that the content of pollutants in plants growing at an altitude of > 400 m a.s.l. is almost 2–3 times higher than in the valleys. This may be related to the Arctic Atmospheric Boundary Layer (ABL) and the so-called "pollutant fog deposition". The prevalent presence of fog/cloud at a given altitude may be crucial in the accumulation of pollutants and affect the width of annual increments (Myśkow *et al.* 2019). Pollutant concentrations in clouds or fog are usually several times higher than in atmospheric precipitation (Błaś *et al.* 2012). Research conducted in the Sudetes Mountains, near the upper forest limit, indicates that total pollutant deposition consisted of 35–50% direct deposition from fog and clouds. In nearby lowland areas, by contrast, this proportion was just 5% (Błaś *et al.* 2008).

Research on long-range transport (LRT) of atmospheric pollutants shows that their transport and deposition depend on mesoscale atmospheric circulation mechanisms, the characteristics of the atmospheric boundary layer and climate, and orography (Dore *et al.* 1999; Błaś *et al.* 2012). These factors lead to significant vertical variations in the deposition of pollutants, particularly at the interface between the vertical thermal inversion and ABL. This is particularly evident in the base zone of lower-level clouds and orographic clouds and fog. Changes in the height of the ABL and in the air temperature in the vertical profile mark the boundary between the dynamics of processes involved in cloud development and the surface radiation budget. As a result, the structure of the ABL modifies precipitation chemistry and the dynamics of other meteorological processes, *e.g.*, water income from the atmosphere. The Arctic is characterised by stable ABL (Kral *et al.* 2021). Consequently, there is no vertical cloud development, and stratus and stratocumulus clouds prevail. These clouds often have a base at an altitude of 400–600 m a.s.l., *i.e.*, at the boundary of the mixing layer (Fig. 6) (Kilpeläinen *et al.* 2012; Maturilli and Ebell 2018; Maturilli 2022; Suomi *et al.* 2025). This relatively low ABL elevation is observed in summer, while in spring the ABL can reach up to 1000 m (Cheng-Ying *et al.* 2011).

In the process of cloud formation, natural and anthropogenic atmospheric pollutants act as condensation nuclei, while the clouds themselves trap the dry fraction of transported pollutants. It is in the zone where lower-level clouds form and occur, at an altitude of 400–600 m a.s.l., that pollutants are captured and concentrated (Fig. 6). This mechanism, originally proposed by Bergeron (1965) is known as the "seeder – feeder effect". This

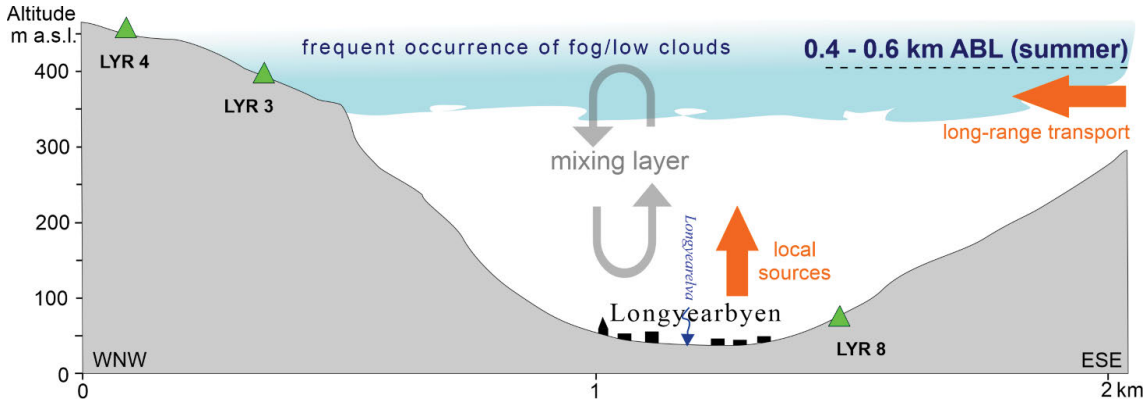


**Fig. 6.** Schematic cross-section through the Longyearelva valley showing the location of research sites and the height of the Arctic Atmospheric Boundary Layer (ABL) during the summer season.

mechanism typically causes an increase in precipitation relative to the lower elevation (Dore *et al.* 1999; Błaś *et al.* 2012). Because of this mechanism orographic cloud droplets are scavenged by upper-level precipitation leading to a significant increase of both precipitation and pollutant deposition. Heavily polluted cloud and fog droplets are deposited on the ground as precipitation or atmospheric deposits. These droplets can make a significant contribution to the water balance, and by supplying plants with water they can introduce pollutants such as heavy metals or sulphur compounds into them. The deposition of fog pollutants can directly damage tissue, causing erosion of waxy coatings and lesions. This can lead to leaf yellowing and, consequently, reduced growth (Myśkow *et al.* 2019).

There are some uncertainties associated with the lack of data on fog chemistry or the influence of microtopography, which can modulate bioavailability. However, these doubts can be reduced by pairing tissues with co-located soil/snow/fog chemistry and meteorology, standardizing shrub size/age, and periodically resampling marked shrubs.

## Conclusions

For the first time in the Arctic, our research indicated increased metal accumulation in *Salix polaris* tissues at higher elevations, which is consistent with enhanced fog and low-cloud deposition. This phenomenon can be linked to the Arctic Atmospheric Boundary Layer and the so-called "pollutant fog deposition". It should be noted that our findings are proposed based on consistency between the spatial pattern of metal accumulation and topographical and meteorological conditions rather than direct confirmation by measurements of fog chemistry, precipitation, aerosols or atmospheric deposition. Previous studies on metal accumulation in plants have focused on the impact of local pollution sources without analysing the vertical distribution of contamination. Across the gradient, metal concentrations in *S. polaris* were higher at high elevation and lower at the valley floor, most clearly in bark. Therefore, this part of the plant, as a bioindicator of pollution, should be taken into account first and foremost when assessing the condition of the natural environment. On average, metal content in bark and wood in shoots and roots at 420–460 m a.s.l. were 2–3 times higher than at the valley bottom. The pattern is consistent with enhanced delivery via polluted fog/low-cloud interception at higher elevations, superimposed on local dust resuspension. These significant levels of metal contamination may affect the growth of polar willow and reduce the width of its annual growth rings, although this is obviously exacerbated by harsh climatic conditions. Further detailed research is needed to clarify these uncertainties, covering not only parts of the plant, but the annual growth rings themselves in particular. Based on the discovered relationships, it is proposed that monitoring of heavy metal concentrations in the Arctic environment should be expanded to include analysis of the height of the Arctic Boundary Layer, in order to determine the potential for increased pollution levels at higher altitudes.

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