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Impacts of Mineral Dust on Trace Element Concentrations (As, Cd, Cu, Ni and Pb) in Lichens and Soils at Lhù'ààn Mân' (Yukon Territory, Canada)

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Key Points:

- Dust deposition, indicated by high trace element concentrations, is higher closest to the delta of the Ä'äy Chù' into Lhù'ààn Mân'
- Evidence for dust deposition at Lhù'ààn Mân' can be found in trace elements of the 0–2 cm soil layer and lichens influenced by distance
- Vegetation characteristics are impacted by dust deposition more than soil characteristics

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Dust is a mineral aerosol of the atmosphere that often contains trace elements such as As, Cd, and Pb. Lhù'ààn Mân' (Kluane Lake), located in southwestern Yukon, is a region of frequent dust activity. In 2016, the lake level fell due to a dramatic decrease in inflow from glacier meltwater, and the delta of the lake became an important source of dust to surrounding ecosystems. To determine the impacts of dust deposition on vegetation and soil trace element concentrations and characteristics, we sampled the lichen *Peltigera canina* and soil layers at 57 sites along a deposition gradient located 1.4–33.6 km downwind from the principal dust source. Arsenic, Cd, Cu, Ni and Pb in lichens were negatively correlated with the distance away from the dust source, with the highest correlations in Ni and Pb (r^2 = 0.50 and 0.48, respectively). Lichen and tree abundances were negatively impacted by dust deposition, suggesting that dust can affect ecosystem vegetation composition. Starting 8 km away from the dust source, the concentrations of As, Ni, and Pb decreased by more than 50% per km, while Cd and Cu concentrations decreased by more than 40% per km. Overall, within the sampled ecosystems, soil pH is 1.4 times higher in the first 8 km from the dust source while carbon content and nutrients are lower, which implies changes in nutrient availability and cycling in dust-affected ecosystems.

Plain Language Summary The delta of Lhù'ààn Mân' (Kluane Lake), located in southwest Yukon and on the traditional lands of Kluane First Nation, Champagne-Aishihik First Nation, and White River First Nation, is an area where dust often settles and climate change has accelerated the melting of glaciers since the last ice age. Due to reduced glacier water flowing into the lake, the sediments in the delta are more exposed to wind, creating dust storms. To understand the impacts of dust deposition within the surrounding ecosystems, we assessed the levels of trace metals in lichens and soils across a gradient from the delta to the lake. We found that distance from the dust source affected trace metal concentrations in lichens, surface soils, and vegetation. It is essential to understand how these metals spread as they can be potentially toxic and harmful to ecosystems and humans.

1. Introduction

Atmospheric dust originates from human activities (mining, gravel roads, etc.) and natural processes (geological and soil erosion, glacier melt) (Bullard et al., 2016; Carling et al., 2017; Csavina et al., 2012; Ravi et al., 2011). Active glaciers produce fine sediments transported by fluvial and aeolian processes as dust (Anderson et al., 2017; Bullard et al., 2016). High latitude cold environments (defined as north of 50°N and south of 40°S) contribute at least 5% of the global dust budget, although their contribution to global dust circulation is seasonally variable (Bullard, 2013; Bullard et al., 2016; Mahowald et al., 2006; Meinander et al., 2022). Glaciers are retreating in most parts of the world due to climate change, and, thus, the valleys they currently occupy could become an important dust source in the coming decades (Bullard et al., 2016).

Dust deposition affects several ecological and biogeochemical processes on scales that range from individual plants to the entire globe (Field et al., 2010). Dust deposition also influences biogeochemical cycles of nutrients (carbon C, nitrogen N, phosphorus P) and trace elements (TE) (e.g., arsenic, copper, lead) in terrestrial and aquatic ecosystems (Bachelder et al., 2020; Das et al., 2013; Formenti et al., 2011; Muhs, 2013; Neff et al., 2008; Swap et al., 1992). For instance, dust deposition represents an important source of N and P in nutrient-limited ecosystems such as the forests in the Amazon and Hawaii (Chadwick et al., 1999; Okin et al., 2004). Dust deposition also appears to impact fundamental terrestrial ecosystem functions such as vegetation composition, soil

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properties, and nutrient cycles (Muhs et al., 2007; Myers-Smith et al., 2006; Okin et al., 2006; Walker & Everett, 1987).

Lichens have been used for monitoring spatial and/or temporal patterns of atmospheric deposition (Bargagli, 2016; Carignan et al., 2002; Klapstein et al., 2020; Simonetti et al., 2003; Sloof, 1995) and for studying long-range transport of trace elements in high latitudes (e.g., Riget et al., 2000; Singh et al., 2013; Wojtuń et al., 2013). Lichens are widespread in boreal and arctic regions, and are slow-growing, perennial organisms that maintain a uniform morphology through time (Bergamaschi et al., 2004; Seaward, 2008). Lichens can accumulate TE and, depending on the lichen species and specific element, can be sensitive to TE exposure (Bargagli, 2016; Nash, 2008; Neitlich et al., 2022; Tyler, 1989). Lichens can also record past and present TE accumulation. For example, Bargagli et al. (2002) showed high arsenic concentrations in lichens (*Parmelia caperata*) near mining and smelting operations in a former industrial district in Italy. Additionally, *Xanthoria parietina* lichens in Southwest France accumulated arsenic and lead from coal combustion during the early twentieth century (Agnan et al., 2013).

The Dhal T'à' (AÄ'ąy Chù' Valley) that connects to Lhù'ààn Mân' (Southern Tutchone name of Kluane Lake) is a high latitude active proglacial landscape with high dust emissions during the spring and summer in the Ä'ąy Chù' River delta, and has been impacted by climate change with the rapid retreat of Kaskawulsh glacier since 2016 (Bachelder et al., 2020; Nickling, 1978; Shugar et al., 2017). This dust is rich in TE including arsenic (As), cadmium (Cd), copper (Cu), nickel (Ni) and lead (Pb) (Bachelder et al., 2020). These TE may come from minerals, as they are present in rocks from the Kluane ultramafic belt or from processes (e.g., rupturing of clay producing fine particulate matter) that releases TE when eroded by wind (Bachelder et al., 2020; Hulbert, 1997; Masuda, 2018).

The goal of this work was to determine the impacts of TE-rich dust deposition on TE concentrations in lichens and soils in a remote area, and to elucidate the implications of this dust deposition for vegetation and soil properties of dust-receiving ecosystems. To do so, we used TE concentration within the microlichen *Peltigera canina* as our main indicator of dust deposition, collected at sites following a depositional gradient around Lhù'ààn Mân'. This lichen of the Peltigeraceae family is associated with cyanobacteria (*Nostoc* spp.), widespread across boreal and subarctic regions (Martínez et al., 2003; Miadlikowska & Lutzoni, 2000) and has a high growth rate (Alam et al., 2015; Beckett et al., 2013; Paulsrud et al., 2001). Lichens have been mostly used to monitor anthropogenic TE deposition in both urban and remote areas (Agnan et al., 2013; Bargagli, 2016; Carignan et al., 2002; Klapstein et al., 2020; Naeth & Wilkinson, 2008; Parviainen et al., 2019; Widory et al., 2018) but there are limited studies on natural deposition in remote areas (Bergamaschi et al., 2004; Darnajoux et al., 2015; Zdanowicz et al., 2017). In an active dust region like Lhù'ààn Mân', it is likely that dust emission would result in higher TE concentrations in *Peltigera* lichens and in underlying soils at closer proximity to the dust source.

2. Materials and Methods

2.1. Site Description

Lhù'ààn Mân' (61°13′03" N, 138°37′34" W, Figure 1a) is located in the Yukon territory between the Ruby Ranges to the northeast and the Kluane Ranges in the St. Elias mountains on the west (Figures 1a and 1b). These lands are traditional territories of Kluane, Champagne-Aishihik, and White River First Nations. The climate is semi-arid, and the area receives a mean annual precipitation of 275 mm, mostly during the summer, with a mean annual temperature of −2.5°C ± 1.1 (1991–2020 climate normal, Canada, E. and C. C., 2011; LaZerte & Albers, 2018), as measured at Burwash Landing. Typically, ∼105 cm of snow falls annually, but it is variable dependent on altitude. Wind velocity and air turbulence can increase transport of sediment in regions where winds often go above 5 m/s (Bullard et al., 2016; Nickling, 1978). At Lhù'ààn Mân', there are strong off-glacial winds (2.0–6.0 m/s) mainly coming from the southeast (Figure 1c). These winds erode the fine sediments of the delta and transport them across the southern part of the lake (Bachelder et al., 2020; Nickling, 1978).

The region is part of the boreal forest biome with white spruce (*Picea glauca*) as the dominant tree type (Crofts et al., 2018; Krebs et al., 2001). The understory is dominated by soapberry (*Shepherdia Canadensis*), and a well-developed ground layer composed of herbs (e.g., *Lupinus arcticus*, *Linnaea borealis, Hedysarum alpinum, Geocaulon lividum*), lichens (e.g., *Peltigera canina*, *Collema tenax*, *Cladonia* spp.) and forest floor mosses such as *Pleurozium schreberi* and *Ptilium crista-castrensis* (Crofts et al., 2018; Douglas & Vitt, 1976; Fremlin

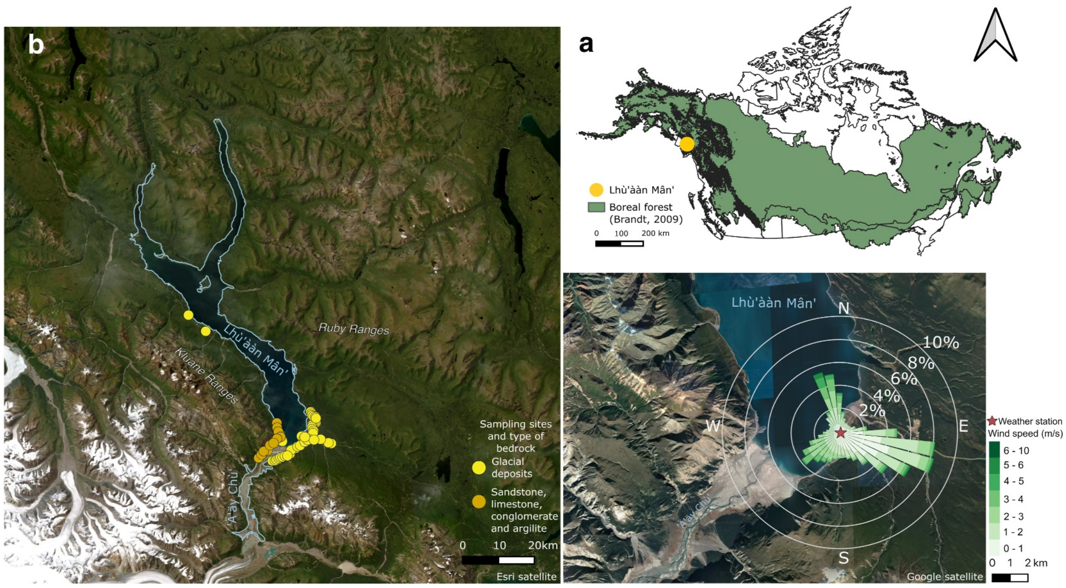

Figure 1. Maps of sampling sites in the Lhù'ààn Mân' (Kluane Lake) region. The three figures are oriented north. (a) Location of the study site Lhù'ààn Mân' in Canada, the boreal forest is defined as the broad, circumpolar vegetation zone of high northern latitudes mainly covered with forests and other cold-tolerant wood species (Brandt, 2009); (b) Location of the sampling sites in Dhal T'à' (Ä'ąy Chù' Valley) and around Lhù'ààn Mân'; (c) Prevailing winds recorded at the weather station of Kluane Lake Research Station (KLRS) between 2017 and 2023 (https://webapp.ccadi.ca/kluane).

et al., 2011; Harris, 1987; Hoefs, 1976; Hoefs & Thomson, 1972; Marsh et al., 2006; Vetter, 2000). Soils within this region have high pH, high calcium carbonate, and an A-horizon rich in organic matter (Laxton et al., 1996). The high calcium carbonate content at the surface reflects the incorporation of neoglacial calcareous loess from the unvegetated floodplains of the Dhal T'à' since deglaciation, about 12,500 B.P (Brahney et al., 2008; Denton & Stuiver, 1967; Hoefs, 1976; Laxton et al., 1996; Marsh et al., 2006). There is also the presence of discontinuous and scattered permafrost soils in the area (Krebs et al., 2001). Sampling sites (orange dots, Figure 1b) in the Dhal T'à' (Ä'ąy Chù' Valley) and on the west part of the lake are on top of sandstone, limestone, conglomerate and argillite (fine grained sedimentary rocks with high clay content) (Israel & Cobbett, 2008; Muller, 1967). These geologic deposits are rich in silica, aluminum, iron, calcium and magnesium minerals. Fine-grained sedimentary rocks such as sandstone, argillite and conglomerate can contain high arsenic concentrations (Masuda, 2018; Tanaka, 1988). High arsenic concentrations are often associated with deposits such as copper, cadmium, lead and nickel (Tanaka, 1988). The glacial till is an eroded feature of those deposits and is the primary source of dust. Sampling sites around the lake (yellow dots, Figure 1b) are within glacial till deposits.

2.2. Sampling

To measure TE concentrations associated with dust deposition and assess its spatial extent, we sampled the terricolous lichen *Peltigera canina* L. Willd. in August 2021 with a stainless-steel knife and scissors, in three replicas, at 57 sites around the lake to capture dust deposition. Sampling sites were located near the roads for accessibility reasons, but the sampling was done at least 100 m from the road, as road dust can affect arctic and subarctic ecosystems especially within the first 50 m from the road (Li et al., 2023; Myers-Smith et al., 2006). In addition to the lichen sampling, two soil layers were sampled, one at 0–2 cm and the other at 2–10 cm in three replicas at each site.

We characterized the percent cover of each vegetation layer (tree, shrub, herb, moss, and lichen layers) within a 20-m radius around the central point of each sampling site. We followed the inventory method recommended by the *Field Manual for Describing Terrestrial Ecosystems* (Erwin, 2010), which is used by the territory (Environment Yukon, 2016, 2017). The tree layer includes at least the three dominant woody species (Lachance et al., 2021). The shrub layer includes at least 90% of woody plants less than 4 m tall; the herb layer includes all herbaceous species; and the lichens and moss layer include all bryophytes and terrestrial lichens occurring on rock and wood (Erwin, 2010).

2.3. Lichen and Soil Analyses

To prepare for the lichen analyses, 200 mg of dried and ground lichen was digested on a block digester in 2 mL of concentrated certified trace metal grade nitric acid (HNO_3) at room temperature for 12 hr and then at 80°C for at least 12 hr. For the analysis of the soils, 25 mg of dried-milled soil was digested in a block digester in 4 mL of concentrated certified trace metal grade HNO_3 and 1 mL of concentrated certified trace metal grade hydrochloric acid (HCl) at room temperature for 12 hr and then at 80°C for at least 12 hr. Triplicate samples were pooled before analysis. Supernatants were filtered at 0.45 μm. Trace elements (As, Cd, Cu, Ni, and Pb) were determined in lichens and soils and minor elements (Al, Ca, Fe, K, Mg, and Mn) in soils by Inductively coupled plasma mass spectrometry (ICP-MS; PerkinElmer NexION 300×, PerkinElmer Syngistix). The ICP-MS analysis run was randomized. We used procedural and instrumental blanks to quantify a potential contamination during the digestions and analyses. The Ontario Geological Survey 1878P certified fen peat reference material (Riley, 1989), QCS-3 and SCP-QC4, were used in quality assurance and control procedures for the lichens with a recovery rate between 94% and 100.8% (Table S1 in Supporting Information S1). SCP-QC3 and QCS-27 was used for the soils with a recovery rate between 92.5% and 114.0% (Tables S2 and S3 in Supporting Information S1).

Total C and N content in lichens and soils were analyzed on 2 and 5 mg of dried-milled samples, respectively, by CHNO-S elemental analysis (Fisons - EA-1108 CHNS-O Element Analyzer). Total P content was analyzed using a Shimadzu UV spectrophotometry using a colorimetry assay based on the Murphy and Riley method (Murphy & Riley, 1962). We prepared a soil solution with a ratio of 1:10 for the 0–2 cm layer and a ratio of 1:2 for the 2–10 cm layer to measure the pH (Fisher Accumet pH Meter AB 150).

2.4. Statistical and Spatial Analyses

Statistical analyses were performed using *R* version 4.2.2 (R Core Team, 2022) and RStudio 2023.6.1.524 (Posit team, 2023). All data was assessed for normality using Shapiro-Wilk tests because the data should be as close as possible to the condition of normality for parametric analyses (Borcard et al., 2018). The relationships between variables influencing TE concentrations in lichens and soils were evaluated using parametric Pearson's (r^2) correlations to compare non dimensionally homogeneous quantitative variables (Borcard et al., 2018). To determine the changes in ecosystem functions linked to dust deposition, redundancy analyses (RDA) were performed using site characteristics (slope, orientation of the site, and distance) and TE concentrations in lichens (As, Cd, Cu, Ni, and Pb) with environmental variables following methods within Fritze et al. (1989).

Ordinary exponential kriging was considered a suitable way to represent TE concentrations at Lhù'ààn Mân' because it is the principal geostatistical technique that can be used to predict TE concentration in un-sampled locations (Orton et al., 2009; Wackernagel, 2003). Kriging is a statistically based estimator of spatial variables with three components (Bolstad & Manson, 2022). The first component is the spatial trend that depends on the direction, the second component describes the local spatial autocorrelation and the third component is random, stochastic variation (Bolstad & Manson, 2022). All ordinary exponential kriging was performed in RStudio, using the version of *R* previously described. The settings are available in Table S4 in Supporting Information S1. All the maps were made using QGIS 3.30.1 (QGIS Development Team, 2023).

3. Results

3.1. Trace Elements in Lichens

Trace element concentrations in lichens decrease with distance from the dust source (Figures 2 and 3). Indeed, the correlation analysis shows that the distance from the dust source as the most important factor influencing TE concentrations in lichens (Figure S1a in Supporting Information S1). At 8 km or more from the dust source, TE concentrations decrease by more than 50% per km, except for Cu and Cd (Table S5 in Supporting Information S1). Among the TE, As, Ni, and Pb have the strongest statistically significant relationships with distance from the dust source ($r^2 = 0.44$, 0.50, and 0.48, respectively; $p < 0.01$), while concentrations of Cd and Cu have relatively weaker but still significant relationships with distance from the dust source ($r^2 = 0.38$ and 0.25 respectively; $p < 0.001$; Figure 3).

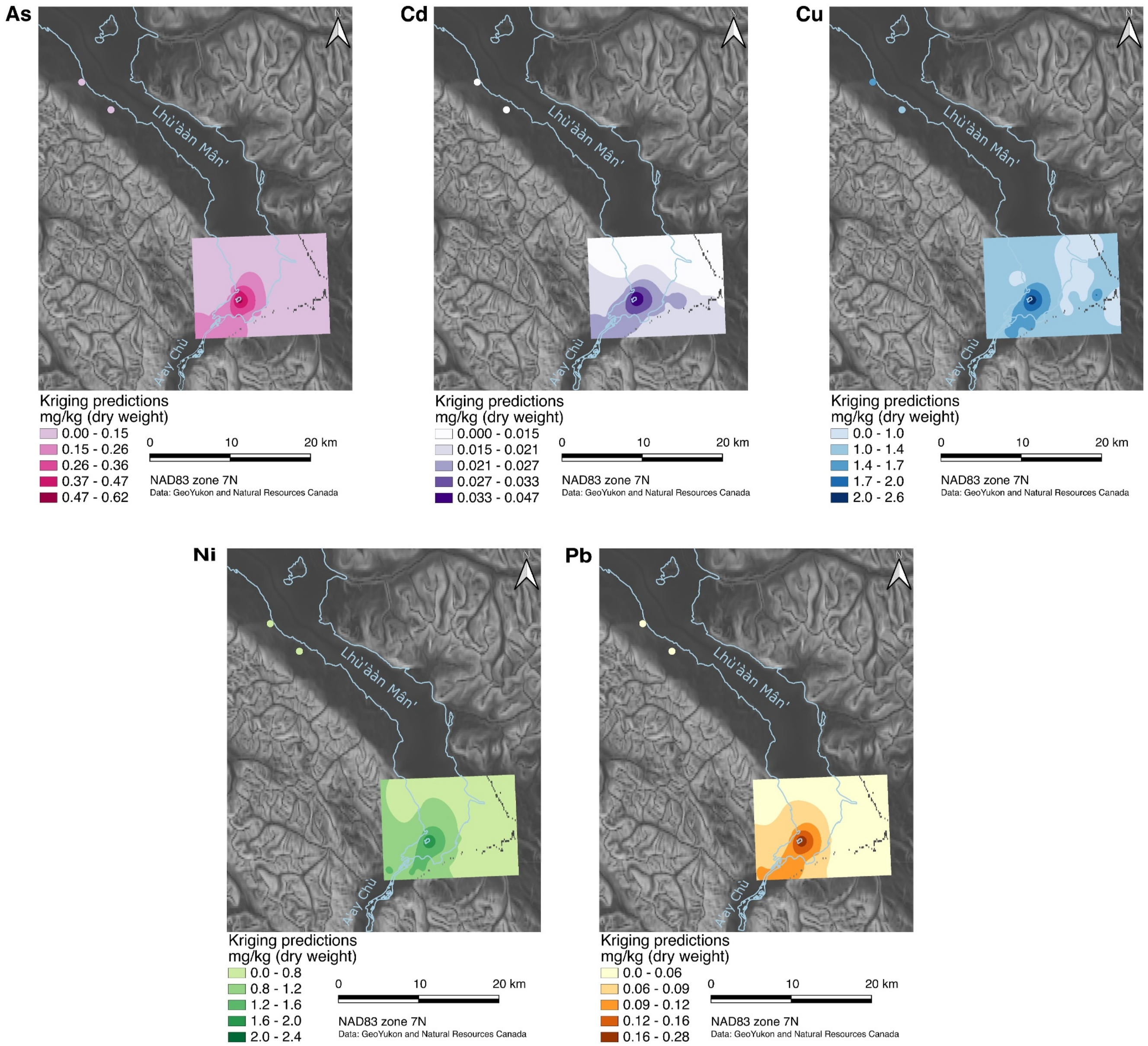

Figure 2. Prediction maps of trace elements concentrations in lichens (*Peltigera canina*) based on ordinary interpolation. Concentration levels are classified into five intervals. Note that the interval range of values differs by trace element.

3.2. Trace Elements in Soils

Arsenic, Ni and Pb concentrations in the 0–2 cm layer decrease with distance from the dust source. This suggests distance has an influence on TE concentrations in the 0–2 cm layer (Figure 4). In contrast, TE concentrations in the 2–10 cm layer are not correlated with distance except for Cu concentrations (Figure 5).

3.3. Impacts on Soil Characteristics

Within this work, we categorize soil characteristics as follows: pH, base cations (Ca, K, Mg, Na), iron (Fe), aluminum (Al), carbon (C), nitrogen (N) and phosphorus (P). The RDA of the 0–2 cm layer characteristics indicates that 37.7% of the variation in the 0–2 cm layer characteristics is explained by TE concentrations in lichens, distance from the dust source, elevation, slope, and orientation of the site ($p = 0.001$; Figure 6a). Axis 1 explains 62.8% of the variance ($p = 0.001$) and is most closely associated with Cd concentrations and distance. Axis 2

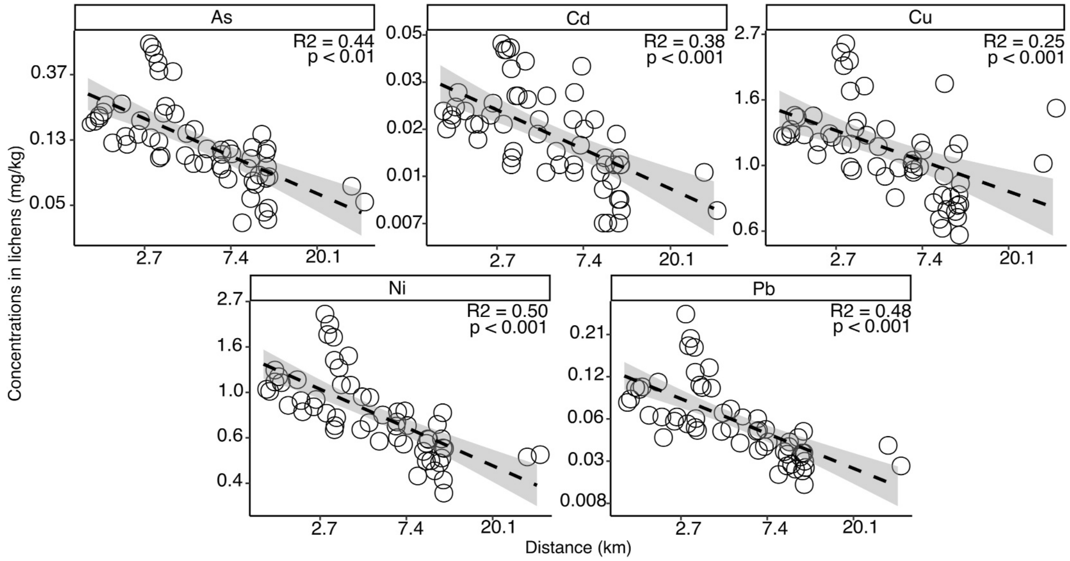

Figure 3. Trace elements concentrations in lichens (mg/kg) versus distance from the dust source (km). R^2 and p values are derived from the non-spatial linear regressions. Dashed lines depict statisticallysignificant curves. The shading shows the 95% confidence interval.

explains 21.4% of the variance ($p = 0.011$) and is associated with orientation and slope. Concentrations of As, Cu, Ni, and Pb in lichens and elevation contribute more to axis 1 as indicated by higher eigenvalues ($\lambda = 5.39$ and $\lambda = 1.83$ respectively).

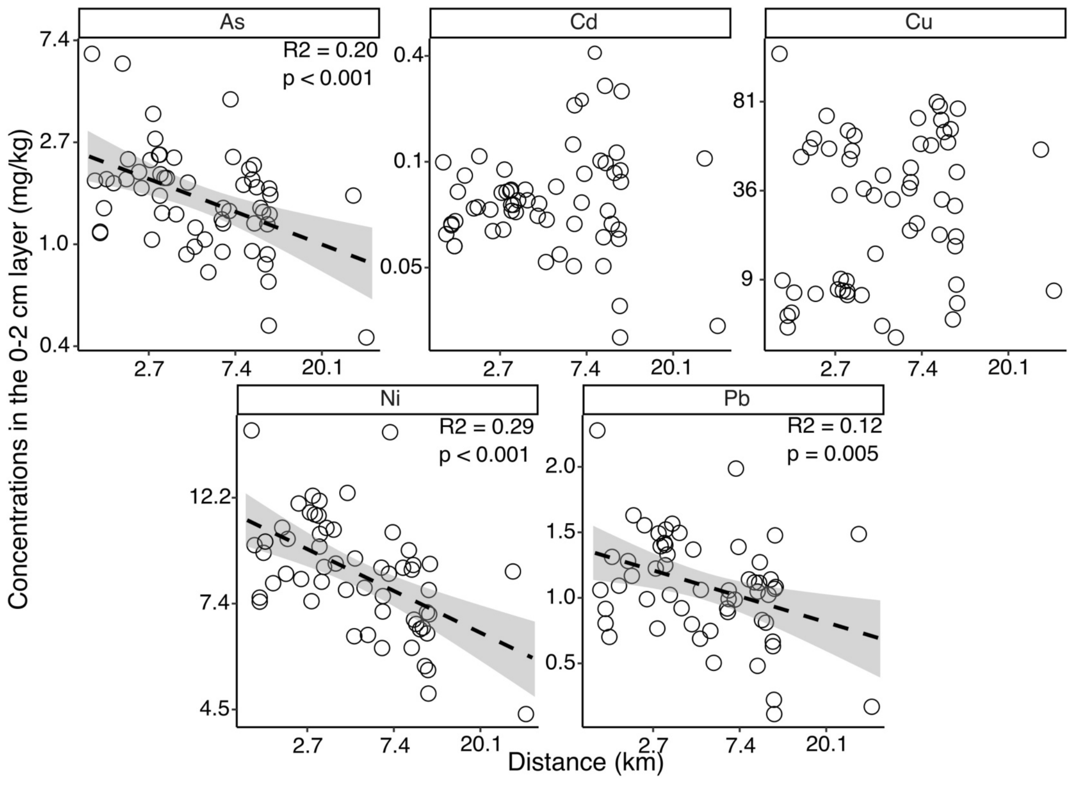

Figure 4. Plots of trace element concentrations in 0–2 cm layer (mg/kg) versus distance from the dust source (km). R and p values are derived from the non-spatial linear regressions. Dashed lines depict statistically significant curves. The shading shows the 95% confidence interval.

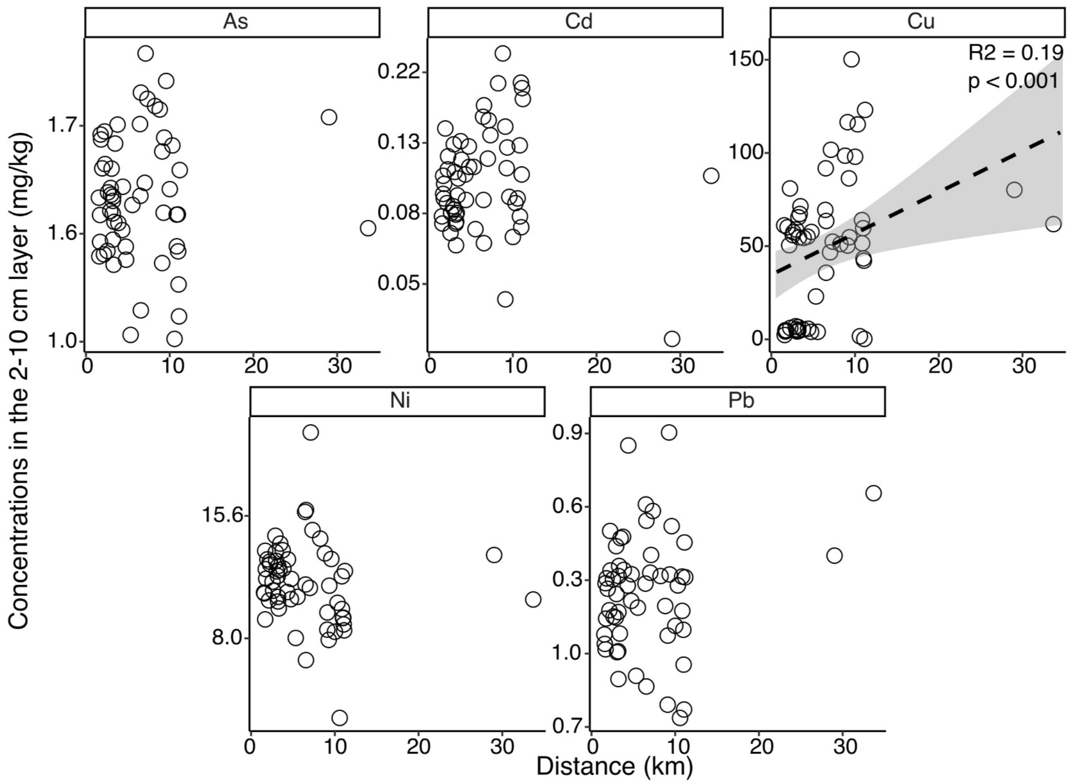

Figure 5. Plots of trace element concentrations in the 2–10 cm layer (mg/kg) versus distance from the dust source (km). R and p values are derived from the non-spatial linear regressions. Dashed lines depict statistically significant curves. The shading shows the 95% confidence interval.

However, the RDA of the 2–10 cm layer characteristics shows that 27.9% of the overall variation in 2–10 cm characteristics is explained by the environmental variables ($p = 0.001$; Figure 6b). Axis 1 explains 51% of the variance ($p = 0.001$) and is associated with distance from the source, Pb and Ni concentrations in lichens. Axis 2 explains 24.9% of the variance ($p = 0.017$) and is associated with slope and orientation. Concentrations of As, Cu, and Cd in lichens, and elevation contribute more to axis 1 ($\lambda = 3.62$) than to the axis 2 ($\lambda = 1.76$).

Soil characteristics are also influenced by the distance from the dust source. pH of the soil shows negative correlations with distance in both the 0–2 cm and 2–10 cm layers (Figures 6a and 6b). However, this negative correlation is weaker in the 2–10 cm layer compared to the 0–2 cm layer, suggesting pH of the 0–2 cm layer is more influenced by dust deposition (Figures 6a and 6b). In the 0–2 cm layer, carbon concentrations increase with distance and decrease with TE in lichens whereas in the 2–10 cm layer, carbon concentrations decrease with distance from the dust source (Figures 6a and 6b). As for nutrients, N and P increase with distance from the dust source in both the 0–2 cm and 2–10 cm layers (Figures 6a and 6b).

3.4. Impacts on Vegetation Characteristics

The RDA of the vegetation shows that 11.08% of the overall variance in vegetation layers is explained by environmental variables, namely TE concentrations in lichens, distance from the dust source, elevation, slope, and orientation of the site ($p = 0.01$; Figure 7a). Axis 1 explains 63.7% of the variance ($p = 0.01$) and is most closely associated with Cd concentrations and distance. Axis 2 explains 22.4% of the variance and is associated with slope and orientation, although these last two variables are not significant ($p = 0.7$). Additionally, concentrations of As, Ni and Pb, along with elevation contribute more to axis 1, as indicated by a higher eigenvalue ($\lambda = 0.80$) compared to the eigenvalue of axis 2 ($\lambda = 0.25$). As a result, lichen and tree cover exhibit a negative correlation to TE concentrations while shrub and herb cover are positively correlated with TE concentrations.

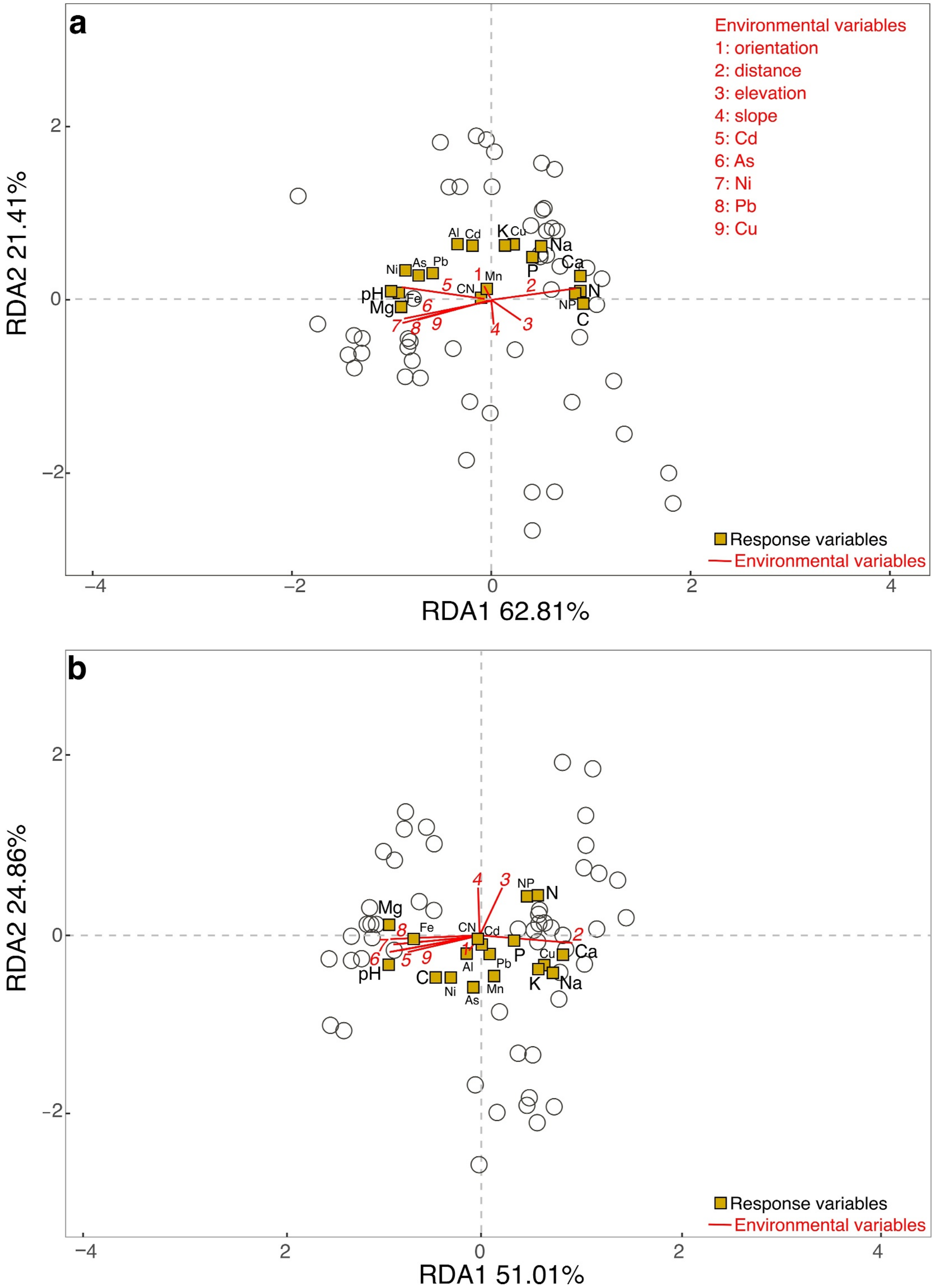

Figure 6. Triplots of redundancy analysis (RDA, scale 2) showing the influence of environmental variables (site characteristics and trace elements in lichens, red lines) on (a) 0–2 cm and (b) 2–10 cm layer characteristics (response variables, orange squares) at 57 sites (bullets).

The RDA between the C and macronutrient chemistry of lichens and environmental variables shows that 26.9% of the overall C, N, and P variation is explained by the environmental variables ($p = 0.001$; Figure 7b). Among these variables, concentrations of As, Cu, Ni and Pb contribute to 55.37% of this variance ($p = 0.003$) while slope and

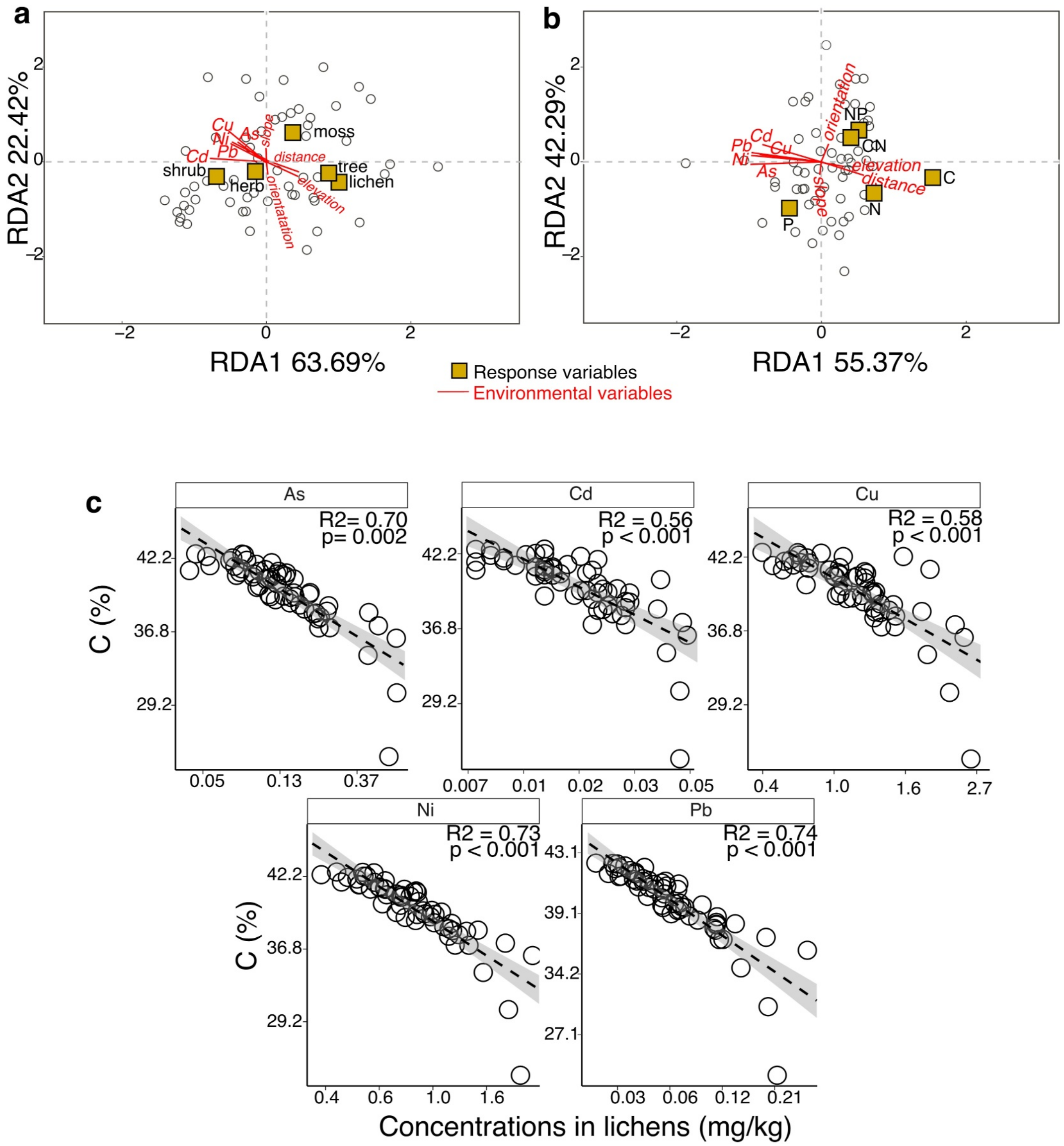

Figure 7. Relationships between vegetation characteristics and environmental variables. (a) Triplot of the redundancy analysis (scale 2) showing the influence of environmental variables (site characteristics and TE in lichens, red lines) on vegetation cover (response variables, orange squares) at 57 sites (bullets). (b) Triplot of redundancy analysis (scale 2) showing the influence of environmental variables (site characteristics and TE in lichens, red arrows) on carbon, nitrogen, and phosphorus concentrations (response variables, grey squares). (c) Plots of carbon (%) in lichens versus TE concentrations in lichens (mg/kg). Dashed lines represent statistically significant relationships. The shading corresponds to confidence interval (0.95).

orientation contribute to 42.3% ($p = 0.034$). Cadmium concentrations in lichens, distance from the dust source, and elevation contribute more to axis 1, indicated by a higher eigenvalue ($\lambda = 1.07$) than the eigenvalue of axis 2 ($\lambda = 0.82$). Trace element concentrations negatively influence C and N concentrations in lichens whereas P concentrations, CN and NP ratios are weakly or not correlated. Distance from the dust source is positively correlated to C and N concentrations. Specifically, carbon concentrations in lichens decrease as TE concentrations in lichens increase (Figure 7c). This correlation is stronger for As, Ni, and Pb ($r^2 = 0.70$, 0.73 and 0.74 respectively) than the correlation between Cd and C ($r^2 = 0.56$) and Cu and C ($r^2 = 0.58$).

4. Discussion

4.1. Trace Elements in Lichens and Soils

With the exception of Cu, TE concentrations are all below 5.0 mg/kg in our vegetation samples (Figure S2 in Supporting Information S1), which indicates that our sites are exposed to limited atmospheric pollution compared to other studies on fugitive dust in mining (Neitlich et al., 2017, 2022; Simonetti et al., 2003). Therefore, we interpret TE signatures to be regionally produced in the Lhù'ààn Mân' region, rather than transported from distal sources. We have found increased concentrations of TE within *Peltigera* lichens closer to the dust point locale (the exposed Lhù'ààn Mân' delta). Based on results from kriging interpolation (Figure 2), As, Cd, Cu, Ni, and Pb concentrations in lichens decrease with distance from the exposed delta. This suggests that there is less dust deposition with increased distance from the source, which can be due to the physical distance from the dust source, or other factors like wind characteristics and size of dust particles (Huang et al., 2021; Myers-Smith et al., 2006; Walker & Everett, 1987). Dust emission mainly depends on the wind velocity giving sufficient kinetic energy to remove fine-grained and coarse material from soil and transport them (Brahney et al., 2014). In Lhù'ààn Mân', wind erosion impacts the rupture of clay mineral coatings and transports them a short distance (Bachelder et al., 2020; Nickling, 1978).

TE concentrations in lower soil layers were not correlated with TE concentrations in lichens and/or distance from source (Figure 3), with the exception of Cu concentration, which was positively correlated with distance. The enrichment of Cu in the layer (2–10 cm) with distance could be due to a leaching from high Cu concentrations in the 0–2 cm layer. Indeed, the 0–2 cms of the Lhù'ààn Mân' region are mostly composed of silt and carbonates with calcium, a competitive ion, which might not allow a high retention of Cu (He et al., 2006; Hoefs, 1976; Laxton et al., 1996; Steinnes & Friedland, 2006). Cu is also more abundant in the soil and dust samples (Figure S2 in Supporting Information S1) because of the presence of native copper deposits in the region (Muller, 1967). Thus, localized biogeochemical factors control the observed patterns of Cu concentrations at Lhù'ààn Mân'.

4.2. Impacts on Additional Soil Characteristics

At Lhù'ààn Mân', the 0–2 cm soil characteristics are not only influenced by TE deposition (Axis 1, Figure 6a) but also by landscape features such as slope, elevation, and orientation (Axis 2, Figure 6b). Dust deposition can have an important effect on pH in 0–2 cm horizons through alkalinization and leachate (Gill et al., 2014; Myers-Smith et al., 2006; Walker & Everett, 1987). We found an increased pH closer to the dust source (Figure 6a) which suggests an alkalinization of the 0–2 cm layer induced by dust deposition. However, this finding is not supported by higher amounts of total Ca as well as other cations close to the dust source, except for Mg (Figure 6a). This could be due to other factors controlling soil pH like the presence of geologic deposits low in Ca at sites close to the dust source (orange dots; Figure 1b).

Dust deposition can also reduce the accumulation of organic matter (OM) in soils as a result of changes in vegetation composition, ecosystem productivity, concentrations of exchangeable base cation, and pH (Auerbach et al., 1997; Johnston & Johnston, 2004; Whittinghill & Hobbie, 2012). In the 0–2 cm layer, carbon concentrations are higher at sites located further away from the dust source (Figure 6a), potentially due to a dilution effect or a direct effect of dust deposition on OM accumulation. Forbes (1995) showed short term responses of tundra vegetation abundance, contributing to organic matter content, and soils to aeolian dust deposition. Dust is likely to accumulate into larger pools in the organic soil horizons over time (Neitlich et al., 2017) and can lead to decrease in the organic matter content over several years. The highest C concentrations are located at sites where elevation is the highest (Figure 6a) likely indicating a lower OM decomposition at sites at high elevation (Badía et al., 2016; Griffiths et al., 2009). Thus, dust deposition is not the only driver of OM content in Lhù'ààn Mân' soils.

In the 2–10 cm layer, the dominant influences on soil characteristics are elevation and slope (Figure 6b) indicating that the 2–10 cm layer characteristics do not depend on dust deposition but mainly depend on landscape features like underlying geology. For instance, the negative relationship between pH in these soil layers and slope (Figure 6b) suggests an accumulation of bases that might have been leached from the top (Ibanga et al., 2008; Khan et al., 2013). We observed an unexpected decrease of base cation (Ca, K and Na) concentrations in the 0–2 cm and 2–10 cm soil layers when closer to the dust source (Figures 6a and 6b) whereas other studies found an increase of base cations with dust deposition (Johnston & Johnston, 2004; Myers-Smith et al., 2006). This decrease could be due to a higher water content accelerating the leaching of Ca, K and Na in the soil layers closer to the dust source (Che et al., 2021; Harris, 1990; Sauer et al., 2007). In the Ä'ąy Chù' delta, the soluble salts are dominated by Ca, with K and Na in lesser amount (Harris, 1990; Nickling, 1978). These salts tend to be concentrated at the surface in early summer as the soils dry out and can bond to soil particles (Harris, 1990; Nickling, 1978). The observed decrease in Ca, K and Na concentrations in the soils could also be explained by runoff of meltwater in the spring or wind transport of salts along with the silt loam particles during erosion of loess (Harris, 1990). High concentrations of Ca, K and Mg would suggest that surface soil characteristics are strongly influenced by dust deposition, while the characteristics of the sub-surface horizons are more likely to depend on the weathering of the local bedrock and landscape features (Johnston, 2001; Johnston & Johnston, 2004).

4.3. Impacts on Vegetation Characteristics

Dust deposition can affect vegetation composition and productivity of arctic and mountainous ecosystems (Auerbach et al., 1997; Gill et al., 2014; Müllerová et al., 2011). Yet, it is known that elevation can also exert a strong control on vegetation distribution (Normand et al., 2009). Tree coverage usually decreases with elevation in response to low temperatures and decrease in tree growth (Griffiths et al., 2009; Testolin et al., 2020). Low tree abundances with higher concentrations of As, Cd, Cu, Ni and Pb would suggest that the vegetation patterns in Lhù'ààn Mân' are also influenced by dust deposition (Figure 7a).

Lichens and evergreen tree species are highly sensitive to dust and TE deposition (Conti & Cecchetti, 2001; Cornelissen et al., 2001; Myers-Smith et al., 2006). In Lhù'ààn Mân', TE concentrations in *Peltigera* lichens are good indicators of their exposure to dust deposition. The negative relationship between trace element concentrations with lichen and tree abundances suggests higher TE concentrations might induce lichen and tree losses within the ecosystem (Figure 7a). However, dust may also impact vegetation growth through shading and mechanical effects, limiting photosynthesis activity (Cornelissen et al., 2001; Mandre & Ots, 1999).

Previous studies assessed the impact of calcareous dust deposition from gravel roads on acidophilic vegetation in the arctic tundra, finding losses of about 50% of lichens (*Cladina* spp and *Peltigera* spp) and evergreen species (Gill et al., 2014; Hope et al., 1991; Moorhead et al., 1996; Myers-Smith et al., 2006; Walker & Everett, 1987) with increased TE from dust. These losses were mainly due to pH and shade increase for lichens, and physical damage or bark chemistry changes for evergreen species (Farmer, 1993; Gill et al., 2014; Myers-Smith et al., 2006; Santelmann & Gorham, 1988; Walker & Everett, 1987). Direct smothering can also cause physical damage to all plant species when exposed to dust (Neitlich et al., 2022).

Shrubs and graminoids are more resilient to dust deposition and variations in soil chemistry (Farmer, 1993; Myers-Smith et al., 2006; Walker, 1996). The negative relationship observed between shrub and herb abundances with distance in Lhù'ààn Mân' (Figure 7a) provides evidence that dust is likely increasing shrub and graminoid growth at sites closer to the dust source. The colonization of graminoids and shrub species might alter N and P availability and allow for higher turnover rates within the local boreal forest ecosystem in which biogeochemical conditions are already limited by nutrient availability (Farmer, 1993; Forbes et al., 2001; Myers-Smith et al., 2006; Walker & Everett, 1987). Additionally, closed canopies can negatively impact shrub and herb abundances in forests through excess shade or varied vegetation successions (Bret-Harte et al., 2001; Chapin et al., 1995; Gill et al., 2014; McTainsh & Strong, 2007; Myers-Smith et al., 2006; Walker & Everett, 1987).

Many moss species are especially sensitive to dust and TE deposition (Auerbach et al., 1997; Farmer, 1993; Hope et al., 1991; Myers-Smith et al., 2006). For instance, peatland mosses (*Sphagnum* sp) have been shown to be very sensitive to calcareous and metal deposition from roads in the Alaskan Tundra and in New Brunswick, and to changes in soil pH (Auerbach et al., 1997; Farmer, 1993; Myers-Smith et al., 2006; Walker & Everett, 1987). In this context, mosses can be less abundant or even die after calcareous atmospheric deposition (Hope et al., 1991; Myers-Smith et al., 2006; Walker & Everett, 1987). However, we found no correlation between moss abundance and distance (Figure 7a and Figure S1a in Supporting Information S1). This suggests that the boreal forest mosses found at our sites (*Pleurozium schreberi* and *Ptilium crista-castrensis*) are less sensitive to dust and TE deposition than expected, but they can be sensitive to other environmental variables (Tobias & Niinemets, 2010). This lower sensitivity of bryophytes than lichens to dust and TE deposition was also reported at Red Dog in northern Alaska (Neitlich et al., 2022). We also found a negative relationship between mosses and shrubs, and mosses and herbs (Figure 7a and Figure S1a in Supporting Information S1) indicating that competition between species, access to the light, and litter fall could have a bigger impact on mosses growth in the boreal forest of Lhù'ààn Mân' than dust deposition (Tobias & Niinemets, 2010).

Dust can be an important contributor of rock-derived nutrients (base cations and P) to ecosystems in arid and semi-arid regions (Arvin et al., 2017; Brahney et al., 2014). In our study, concentrations of P in lichens were not correlated to distance (Figure 7b) which could indicate that dust does not bring P into vegetation at Lhù'ààn Mân' despite the ability of *Peltigera* lichens to accumulate high P concentrations in their thalli (Asplund & Wardle, 2017) or that the trends shown are insignificant relative to the input expected from dust. For example, P concentrations are lower (average of 443 mg kg^{-1}) in Lhù'ààn Mân' soils compared to P concentrations (3,000 mg kg^{-1}) in dust and lake sediments (1,000–5,000 mg kg^{-1}) in the Wind River Range watershed in Wyoming reported by Brahney et al. (2014). Additionally, we found an increase in P concentrations with distance in 0–2 cm and 2–10 cm layers indicating that dust does not bring P into soils Lhù'ààn Mân'. This increase is also correlated with a decrease in pH in 0–2 cm and 2–10 cm layers (Figure 6) suggesting that this patterns may result from acidification, which can enhance chemical weathering of minerals and contribute to P availability (Marsh et al., 2006).

Lichens derive carbon from algal and cyanobacterial photobionts, and are dependent on the availability of nutrients like N, deposited on the thallus or fixed by cyanobacterial lichens (Dahlman et al., 2003). We found carbon and N concentrations in lichens increase with distance from the dust source (Figure 7b) suggesting that N is not deposited in the ecosystem. The high N concentrations measured in lichens in our study might be explained by a large amount of N fixed by *Peltigera* lichens which often occurs in arctic environments (Asplund & Wardle, 2017; Gunther, 1989) thus increasing C concentrations and C assimilation capacity (Palmqvist et al., 2002).

Despite lichens ability to accumulate trace elements, their accumulation can sometimes have a negative effect on photosynthetic activity (Brown & Beckett, 1984). We found that C concentrations in lichens decrease with increased TE concentrations (Figure 7c) suggesting that TE have a negative effect on lichens likely by reducing thallus size, inducing colour darkening colour and causing cell damages (Goyal & Seaward, 1981; Nagy et al., 2005; Pisani et al., 2011). Arsenic concentrations found at Lhù'ààn Mân' are in the range of concentrations from 0.1 to 10 mg/kg that are sufficient to cause physiological stress to lichens (Pisani et al., 2011). Furthermore, Cu concentrations between 20 and 100 mg/kg are considered as excessive contents for uptake and can cause damage to lichens, bryophytes, and vascular plants (Kabata-Pendias, 2010). Toxicity of a trace element depends on the concentration and its forms. Trivalent As (AsIII) is 5–10 times more toxic than pentavalent As (AsV) (Gamberg, 2000). While we did not look at the speciation of arsenic, there are still toxicity concerns with the level of As found within the soils and lichens if exposure continues. Arsenic can accumulate in the liver, kidney, muscle, skin and hair and cause toxic effects for wildlife and humans (Gamberg, 2000; Ratnaike, 2003). Lead may be absorbed by plants through the leaves or from the soil through the roots (Gamberg, 2000; Kabata-Pendias, 2010).

Lastly, we also found that N decreased with increased TE concentrations (Figure 7b) which suggests that TE accumulation might have a negative influence on N_2 fixation by cyanobacteria, induced by reductions in density of cyanobacteria in lichens (Nagy et al., 2005; Pisani et al., 2011). Thus, the chemical composition of dust might impact lichen growth more than the physical deposition of particles.

5. Conclusions

Dust storms are more intense and frequent in the Lhù'ààn Mân' region since 2016 (Bachelder et al., 2020; Huck et al., 2023; Shugar et al., 2017). Dust depositions were evaluated by measuring TE concentrations in lichens downwind from the dust source in the region. Trace element concentrations in lichens and distance from the dust source were negatively correlated suggesting that trace elements in lichens were higher near the dust source, specifically between 1 and 4 km. Beyond 8 km from the Lhù'ààn Mân' delta, these concentrations decrease by over 50% per km. The corroboration of TE in lichens and distance allowed us to determine that using relative TE concentrations in lichens was a suitable approach for evaluating the impact of dust in the region. Arsenic, Cd, and Pb performed better to evaluate dust deposition in this region when compared to Ni and Cu, which are found in the local bedrock. Trace element concentrations in the 0–2 cm layer were more influenced by dust deposition than TE concentrations in the 2–10 cm layer. TE concentrations in 2–10 cm horizons were likely more influenced by the chemical composition of the antecedent bedrock or other geochemical processes like leaching. Overall, soil pH, C content, and nutrients in 0–2 cm and 2–10 cm horizons are the main characteristics impacted by dust deposition in the region.

Vegetation was the main component of the ecosystem affected by dust deposition. Lichens and trees, which are more sensitive to dust, were negatively impacted, while shrubs and herbs were positively impacted. Dust deposition has been shown in this study to impact ecosystem characteristics, specifically on vegetation composition and soil chemistry. Thus, this study contributes to a better understanding of the impacts of dust on trace element concentrations, vegetation, and soil characteristics in glacial regions affected by glacial retreat and climate change.

Data Availability Statement

All the data used to determine the impacts of dust on subarctic terrestrial ecosystems in the study are available in the Pangaea repository (Pouillé, 2024): https://doi.pangaea.de/10.1594/PANGAEA.965325.

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