Institut für Umweltwissenschaften und Geographie

Universität Potsdam

Mathematisch-Naturwissenschaftliche Fakultät
Institut für Umweltwissenschaften und Geographie
B.Sc. Geoökologie

Does large Herbivore Activity influence Mercury Levels in Arctic Soils?

BACHELORTHESIS

Gutachter: M.Sc. Torben Windirsch-Woiwode
Zweitgutachter: Dr. Jens Strauss

Eingereicht von: Anna-Lena Matzander
Matrikelnummer: 803147
Datum der Abgabe: 28.09.2023

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LIST OF ABBREVIATIONS

AWC	absolute water content
BD	bulk density
bs	below surface
C	Celsius
CH	Chersky
cm	centimeter
cor	correlation
et al.	et alias
FI	Finland
g	gram
Gg	gigagram
Hg	mercury
i.e.	that is
kg	kilogram
km	kilometer
m	meter
Max	maximum
MeHg	methylmercury
mg	milligram
MGS	mean grain size
Min	minimum
mm	milimeter
NA	not available
OM	organic matter
PF	permafrost
SD	standard deviation
SEM	standard error to the mean
SIPRE	Snow Ice Permafrost Research Establishment
SFG	seasonally frozen ground
TC	total carbon
THg	total mercury
TN	total nitrogen
TOC	total organic carbon
TOC/TN	carbon-to-nitrogen-ratio
wt%	percentage by weight
δ13C	stable carbon isotope ratio
µg	microgram
µm	micrometer

ABSTRACT

Mercury (Hg), a neurotoxic pollutant of global significance, is stored in high amounts in Arctic grounds, while its deposition in the Arctic further increases. With climate change inducing accelerated permafrost thaw as well as shortened freezing seasons in seasonal frozen ground, this could lead to the re-release of Hg into the environment. For this reason, this study addressed the question of whether differences in activity by large herbivores might correlate with differences in soil mercury content in Arctic ground, due to the ground-cooling effects attributed to the animals. Therefore, soil cores from north-eastern Siberia (permafrost soil) and northern Finland (seasonally frozen soil) from sites with different grazing intensities were analyzed and compared for their mercury concentration. Additionally, depth trends of the cores regarding their mercury content, as well as possible correlations with other variables (total organic carbon, absolute water content and mean grain size) were examined. For a merged data set, grazing intensity did not show a significant correlation with mercury content in the soil, while a decrease with depth was detectable for most cores, which was attributed to decreasing surface influence and the associated input of mercury through the atmosphere, vegetation, animal dung and flooding. Total organic carbon showed the most relevant and highest correlation on the mercury content, due to the adsorbing property of organic matter. A separate consideration of the permafrost ground in Siberia and the seasonally frozen ground in Finland showed clear differences in regard to the influence of herbivore activity. While the animals did not show an effect on the concentration of mercury in seasonally frozen ground, the Siberian permafrost sites showed a clear variation in their mercury concentration between grazed and ungrazed sites. In contrast, a difference between sites with existing grazing but of varying intensity was less pronounced. A cause of this phenomenon was presumed in insufficiently diverse animal density, insufficient sample size, prevailing vegetation, as well as occasional flooding. Nevertheless, the samples from Siberia showed a positive correlation between grazing intensity and mercury, indicating that with higher herbivore activity mercury levels increase and suggesting a more effective fixation of the pollutant in permafrost soil.

ABSTRACT IN GERMAN LANGUAGE / DEUTSCHE ZUSAMMENFASSUNG

Quecksilber (Hg), ein neurotoxischer Schadstoff von globaler Bedeutung, wird in großen Mengen in arktischen Böden gespeichert, während seine Ablagerung in der Arktis weiter zunimmt. Da der Klimawandel zu einem beschleunigten Auftauen des Permafrosts und zu einer Verkürzung der Gefrierzeiten in saisonal gefrorenen Böden führt, könnte dies eine erneute Freisetzung von Hg in die Umwelt bewirken. Aus diesem Grund wurde in dieser Studie der Frage nachgegangen, ob Unterschiede in der Aktivität großer Herbivoren, aufgrund der ihnen zugeschriebenen Bodenkühlungseffekte, einen Einfluss auf die Quecksilberkonzentration in arktischen Böden aufweisen. Bodenkerne aus Nordostsibirien

(Permafrostboden) und Nordfinnland (saisonal gefrorener Boden) von Standorten mit unterschiedlicher Beweidungsintensität wurden analysiert und hinsichtlich ihrer Quecksilberkonzentration verglichen. Darüber hinaus wurden Tiefenentwicklungen der Bohrkerne hinsichtlich ihres Quecksilbergehalts sowie mögliche Korrelationen mit anderen Variablen (gesamter organischer Kohlenstoff, absoluter Wassergehalt und mittlere Korngröße) untersucht. Bei einem zusammengefassten Datensatz zeigte die Beweidungsintensität keine signifikante Korrelation mit dem Quecksilbergehalt im Boden, während bei den meisten Kernen eine Abnahme mit der Tiefe festzustellen war, was auf den verminderten Oberflächeneinfluss und den damit verbundenen Eintrag von Quecksilber über die Atmosphäre, die Vegetation, Tierdung und Überschwemmungen zurückgeführt wurde. Der gesamte organische Kohlenstoff wies aufgrund der Adsorptionseigenschaft organischer Substanzen die wichtigste und höchste Korrelation mit dem vorhandenen Quecksilbergehalt auf. Eine getrennte Betrachtung des Permafrostbodens in Sibirien und des saisonal gefrorenen Bodens in Finnland zeigte deutliche Unterschiede im Hinblick auf den Einfluss der Herbivorenaktivität. Während die Tiere keinen Einfluss auf die Quecksilberkonzentration in saisonal gefrorenen Böden zeigten, wiesen die sibirischen Permafrostböden einen deutlichen Unterschied in ihrer Quecksilberkonzentration zwischen beweideten und unbeweideten Standorten auf. Dagegen war ein Unterschied zwischen Standorten mit vorhandener Beweidung, aber unterschiedlicher Intensität, weniger ausgeprägt. Als Ursache für dieses Phänomen wurden eine zu geringe Tierdichte, eine unzureichende Probengröße, die vorherrschende Vegetation sowie gelegentliche Überschwemmungen in Betracht gezogen. Dennoch zeigten die Proben aus Sibirien eine positive Korrelation zwischen Beweidungsintensität und Quecksilber, was darauf hindeutet, dass der Quecksilbergehalt mit zunehmender Herbivorenaktivität steigt und eine effektivere Fixierung des Schadstoffs im Permafrostboden vorliegt.

1 INTRODUCTION

As a neurotoxic pollutant of global significance, mercury (Hg) can be transported in elemental gas form through the atmosphere over immense distances, reaching remote areas such as the Arctic (Cobbett et al. 2007; Driscoll et al. 2013; Sprovieri et al. 2010), a region of the Northern Hemisphere (defined as the area north of the Arctic Circle at 66.5667°N), in which terrestrial parts are sparsely populated by humans (Emelyanova 2017) and largely undisturbed by direct anthropogenic impacts aside from resource exploitation and forestry, along with some traditional livelihoods such as hunting, gathering, fishing and herding (Nuttall et al. 2005; Juday et al. 2005).

However, although direct anthropogenic influence is low in the Arctic itself, the input of pollutants via atmospheric transport is of high relevance. Compared to pre-industrial background levels, atmospheric Hg deposition in the Arctic increased threefold by the early 2000s (Fitzgerald et al. 2005), while other studies suggest an even larger increase until 2015 (Enrico et al. 2017). Because mercury has harmful effects on wildlife and humans (Atwell et al. 1998), the increase in Hg exposure is a highly problematic development. In particular, the maintenance of traditional livelihoods in relation to the dietary composition of northern peoples raises health concerns (UNEP 2013; Lehnherr 2014).

Polar ecosystems are particularly vulnerable to Hg contamination, especially through cross-trophic-level mechanisms of biomagnification (Atwell et al. 1998). Due to climate change, major environmental transitions are occurring throughout the Arctic, affecting the specific physical, chemical, and biological processes of this unique environment and, consequently, pollutant cycles such as the mercury cycle (Douglas et al. 2012).

Due to Arctic amplification, which has caused surface air temperatures in the Arctic to rise over twice as rapidly as the global mean, this region is experiencing the most pronounced effects of global climate change (Serreze und Barry 2011; Meredith et al. 2019). This trend is anticipated to persist, with future changes expected to further outpace the global average (IPCC 2013). The physical changes to Arctic ecosystems caused by climate change, such as thawing of permafrost (ground frozen for at least two consecutive years, often millenia (Dobinski 2011)) and development of thermokarst (ground subsidence due to thawing of ground ice (Czudek und Demek 1970)), increased river runoff, and more (Post et al. 2009; Perovich und Richter-Menge 2009; Box et al. 2019), are likely to affect the long-term cycling and biogeochemistry of mercury (Stern et al. 2012). Climate change impacts on Hg transport are found in snowmelt, which is considered an important factor in the transfer of Hg to terrestrial and aquatic ecosystems in the Arctic (Obrist et al. 2018; Dommergue et al. 2010), and in increasingly frequent summer rainfalls (Bintanja 2018). However, permafrost degradation also plays a critical role in this context (Chételat et al. 2022).

The top layer of soil above permafrost that thaws in summer and refreezes in winter is called the active layer, while the boundary with the permanently frozen layer is called the permafrost table (Dobinski 2011).

When atmospheric mercury is deposited at the soil surface, it bonds with organic matter (OM) in the active layer (Schuster et al. 2018). Microbial consumption of said OM leads to the release of Hg (Smith-Downey et al. 2010). Sedimentation increases soil depth, causing the OM at the bottom of the active layer to be incorporated into permafrost. Subsequently, microbial decomposition is slowed down and the Hg is fixed within the permafrost. The fact that the storage of Hg in organic carbon has increased by about 20 % since pre-industrial times (Smith-Downey et al. 2010) already indicates the particular relevance of this variable.

Due to climate change, permafrost is thawing at an increasing rate (Hinzman et al. 2005; Smith et al. 2010), which could lead to the re-release of Hg into the environment (Driscoll et al. 2013). Researchers estimate that Northern Hemisphere permafrost areas contain 1656 ± 962 gigagrams (Gg) Hg, of which 793 ± 461 Gg are frozen in permafrost (Schuster et al. 2018). Further, they suggest that permafrost soils store nearly twice as much Hg as all other soils, the ocean, and the atmosphere combined (Schuster et al. 2018). For every 1 °C of warming, a loss of 6 % to 29 % of high-latitude permafrost has been predicted (Koven et al. 2013). Additionally, if anthropogenic greenhouse gas emissions continue to increase at current levels, model projections suggest that the Northern Hemisphere permafrost area will decrease by 30 to 99 % by 2100 (Koven et al. 2013).

However, not only in permafrost soils, but also in Arctic seasonally frozen soils, the freezing season is shortened due to climate warming and increasing snowfall (Chen et al. 2022). In these areas, OM content is available for microbial decomposition and can potentially release mercury.

The Arctic tundra forms a particularly important Hg sink through uptake of gaseous Hg during the summer months (Obrist et al. 2017). Especially non-vascular plant species, notably mosses and lichens, have been shown to take up substantial quantities of atmospheric mercury (Olson et al. 2019). Vegetation in general not only has a substantial influence on climate, with the regulation of the albedo being particularly important at high latitudes (Finne et al. 2023), its composition also plays an important role in controlling Arctic surface, near-surface, and subsurface temperature regimes. By reducing summer energy exchange, creating protection from wind, and establishing a stable air layer between the ground surface and the canopy, dense vegetation can lead to relatively colder ground in summer (Zhang et al. 2013; Mod und Luoto 2016; te Beest et al. 2016).

However, shrub vegetation has been observed to lower the albedo compared to lichen or graminoid-tundra (Juszak et al. 2014), which consequently has a warming effect on the ground, and effectively retains snow in winter, resulting in insulation that keeps the soil relatively warm over this season (Sannel 2020). Graminoid vegetation, on the other hand, favors soil cooling in winter by reducing the volume of air trapped beneath snow (Block et al. 2010). Although the reduced insulative properties of the vegetation layer during summer result in increased soil warming, the prolonged duration of Arctic winters compared to the summer periods allows for compensation within a comprehensive analysis (Windirsch et al. 2022).

Accordingly, for soil cooling and thus more effective fixation of mercury in Arctic soils, graminoid vegetation is preferable.

An impact on vegetation as well as on snow cover can be made by large herbivorous animals (Zimov 2005). Cold ground conditions during the late Pleistocene are thought to have been stabilized by large herbivores (Zimov et al. 1995), as the animals altered vegetation structure by grazing as well as trampling (Tuomi et al. 2021), with reductions in vegetation height in particular influencing the temperature regime (Olofsson et al. 2004; Zimov 2005). With high herbivore activity, shrub abundance could be reduced and contribute to a shift from shrubby tundra vegetation to a graminoid-dominated vegetation (Zimov 2005). This would also lead to an albedo increase and thus lower latent and sensible heat fluxes (te Beest et al. 2016). In addition, large herbivores have an impact on the snowpack in winter by compacting or even partially removing it (Windirsch et al. 2022). This also promotes soil cooling, as the reduced thickness of the insulating layer allows cold winter air temperatures to reach the soil more easily and may even lead to re-freezing (Beer et al. 2020). That herbivores promote lower soil temperatures through the processes described above may slow the decomposition of organic matter (Macias-Fauria et al. 2020; Windirsch et al. 2022).

This raises the question, whether differences in activity by large herbivores might correlate with differences in soil mercury content in Arctic ground. Because more effective cooling could slow or even halt microbial decomposition, allowing harmful mercury to remain fixed in the soil longer, it stands to reason that the soil-cooling effects of herbivores could also have an impact on mercury levels in Arctic ground. Since a release of large amounts of mercury should be prevented due to its described toxic properties, this study focuses on the examination of mercury levels in permafrost and seasonally frozen soils under different intensities of grazing by large herbivores. It was hypothesized that when comparing sites with different levels of grazing pressure on Arctic soils, different mercury concentrations are to be expected. It is assumed that the cooling effect applied to the soil by animal activity results in a higher and more stable mercury storage capacity, along with the animals directly influencing mercury concentrations through input (feces) and uptake (grazing). Within the study areas near Chersky (northeastern Siberia) and Kaamanen (northern Finland) permafrost and seasonally frozen soils are considered separately. It is anticipated that the described trend will occur more significantly in permafrost soils than in seasonally frozen soils due to their more continuous and stable storage capacity. Since upper soil layers show more contemporaneous events, stronger effects are expected here in comparison to the total soil core depth. Because the ground-cooling could provide longer fixation spans of Hg, it is also assumed that with increasing herbivore activity an increase in the soil mercury content would be observable, with a possible increase of mercury with depth.

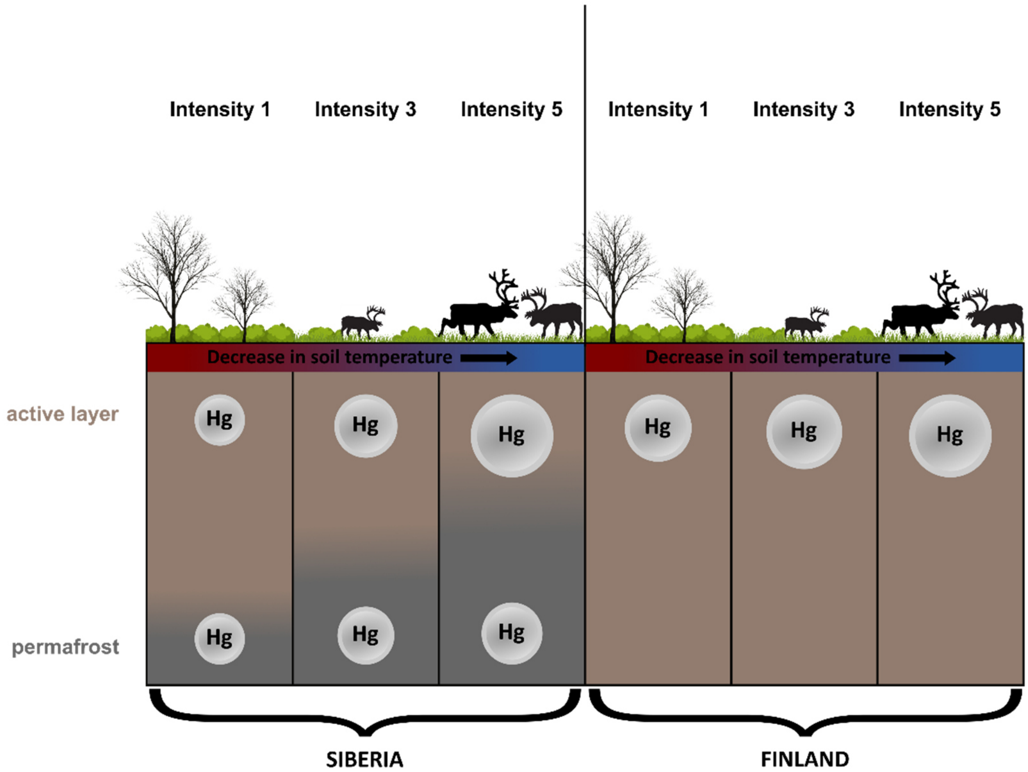

Figure 1: Illustration of the study concept and expected results. *It is assumed that with increasing herbivore activity, resulting in vegetation changes and soil cooling, mercury levels will increase due to more effective soil fixation. Further, this trend is expected to be more pronounced in permafrost soils than in seasonally frozen soils. Below the permafrost table, less variation is expected. Figure 1 is a simplified illustration. The displayed vegetation does not necessarily reflect Arctic vegetation. The illustrated ground cooling trend represents the net cooling. As described earlier, animal activity has opposite effects on soil temperatures at different times of the year.*

2 METHODS

2.1 Study Areas and Sites

The following study is based on sample series collected in 2019 at the Pleistocene Park near Chersky in northeastern Siberia as well as on samples surveyed from the municipality of Inari in northern Finland in 2020 and 2022. The incorporation of different areas such as Siberia and Finland allows for a more differentiated overall picture for possible effects by herbivore activity on mercury concentrations in Arctic soils due to their different soil characteristics.

2.1.1 Siberia

The Pleistocene Park is located in northeastern Siberia and represents an initiative approach for a nature-based solution to climate change by restoring highly productive grazing ecosystems in the Arctic (Pleistocene Park Foundation 2023; Zimov 2005). These grazing ecosystems have a cooling effect on climate and protect Arctic permafrost from degradation. A circumstance that could possibly be highly relevant to soil mercury concentrations.

Experimental reintroduction of animals began in 1988 (Pleistocene Park Foundation 2023; Zimov 2005). At present, reindeer, Yakutian horses, moose, bison, musk oxen, Kalmykian cattle, sheep, camels and goats are established on the closed 20 square kilometer (km^2) area. The presence of these animals already shows an effect on the vegetation within the fenced areas after the first 20 years of the experiment. In addition, the carbon storage in the soil is already slowly increasing while the rate of the nutrient turnover is quickening (Pleistocene Park Foundation 2023).

The area of the Pleistocene Park, which has an approximate distance of 100 kilometer (km) from the Arctic Ocean, is located in the floodplain of the Kolyma River (Fuchs et al. 2021). It shows a number of Yedoma hills cut by deep thermo-erosional valleys and thermokarst depressions (Strauss et al. 2012). Characterized by thermokarst lakes, drained thermokarst basins and plateaus with late Pleistocene ice- and organic-rich permafrost deposits (Schirrmeister et al. 2011), the landscape shows a variety of marshes, river valleys and deltas (Veremeeva et al. 2021). The predominant deposit types are Yedoma and thermokarst (Veremeeva et al. 2021). The latter accounts for about 58 % of the land in areas with high Yedoma coverage and up to 96.4 % of the land in regions with low Yedoma occurrence (Windirsch et al. 2022). Depending on the local moisture gradient and grazing intensity, the vegetation in thermokarst basins is variable. *Carex appendiculata* assemblages spread dominantly in shallow waters and lakeshores. Grasses up to 70 centimeters (cm) tall, *Calamagrostis langsdorfii* and others, grow in frequently flooded areas. Such seasonal floods occur mainly after the snowmelt in spring (Windirsch et al. 2022).

The vegetation assessment that was conducted as part of the pilot study at the 5 sampling sites in Chersky in 2019 found *Calamagrostis langsdorfii* to be the only species in the 1 x 1 meter (m) plot at site B3 with a coverage of more than 95 % (Windirsch et al. 2022). Site B2 was dominated by *Poaceae* with approximately 70 % coverage. However, the *Poaceae* could not be identified on a species level due to a lack of blossoms and herbivory damages. Additionally, a small amount of *Salix ssp.* was present inside the plot (less than 10 %), while *Salix ssp.* and *Larix ssp.* shrubs with a height of up to 2.5 m were found close to it. *Beckmannia syzigachne* was identified as the predominant species at site B1, with an approximate coverage of 65 % and an approximate height of 25 cm. Small amounts of *Saxifraga ssp.*, *Equisetum ssp.* and low-growing *Salix ssp.* grew among them. U3 had much lower-growing vegetation compared to the other sites (up to 15 cm in height), with approximately 50 % of this vegetation consisting of unidentified graminoids. Again, an identification on species level was not possible due to herbivory damage. Also present at this site were *Rubus ssp.* (15 to 20 %), *Saxifraga ssp.* (less than 5 %), *Salix ssp.* (less than 5 %), as well as a few individuals of *Vaccinium ssp.* and *Arnica ssp*. *Salix ssp.* (Windirsch et al. 2022).

Climatically, the region shows large temperature amplitudes with an average of -33 °C in January and 12 °C in July as well as a mean annual temperature of -11 °C (Göckede et al. 2017). Autumn and summer are the main rainfall seasons with August as the month with the highest precipitation (30 millimeters (mm)), in contrast to the driest month March (7 mm). For the annual precipitation 197 mm can be recorded (Göckede et al. 2017).

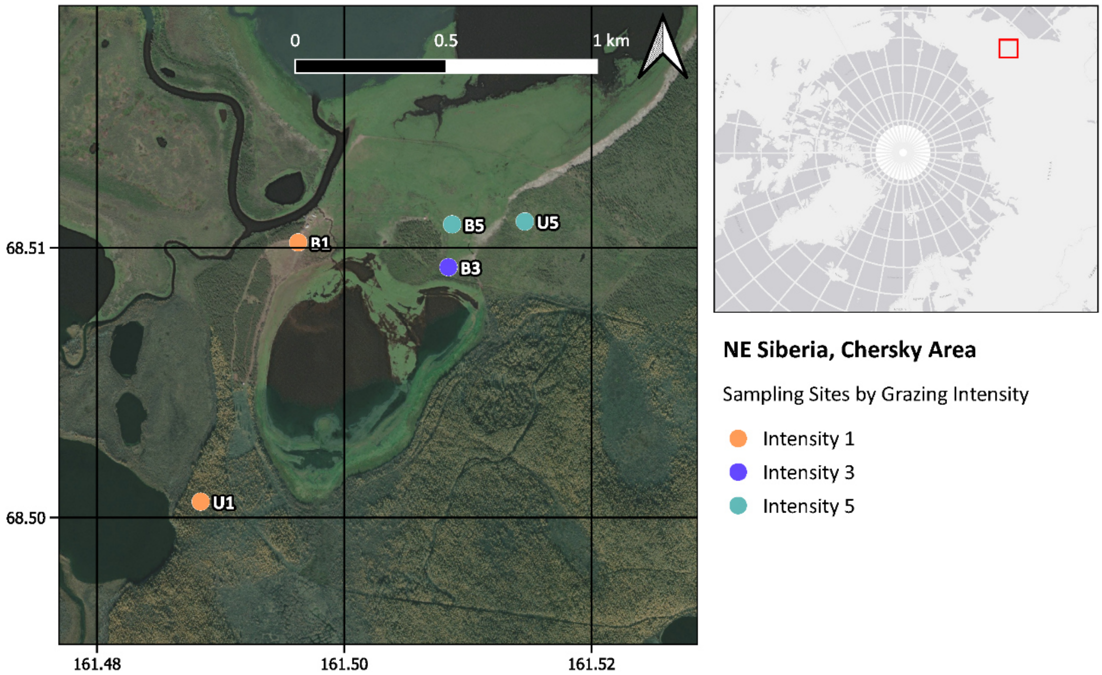

Figure 2: Study Area in NE Siberia, Chersky. *The figure shows the location of the study area in a circumpolar map, marked by the red square, as well as the location of the sampling sites with intensity 1 sites in orange, intensity 3 sites in blue, and intensity 5 sites in green. The map was created using the free geographic information system software QGis. The basemaps were provided by ESRI.*

Figure 2 shows the location of the study area in Chersky. The individual sampling sites have been labeled. The sampling site B5 is located in a drained thermokarst basin, which during seasonal floods occasionally carries water that covers the sampling site (Windirsch et al. 2022).

2.1.2 Finland

The samples from northern Finland are from the municipality of Inari, where the husbandry of semi-domesticated reindeer (*Rangifer tarandus tarandus*) has been the predominant form of land use for centuries (Löf et al. 2022). Originally, this way of life was adapted to the animals' long seasonal migrations between the nutrient-rich coastal areas of Norway in summer and the continental, lichen-rich mountain areas of Finland, Sweden, and Norway in winter (Oksanen und Virtanen 1995). Key factors in reindeer feeding site selection are the availability of forage and avoidance of insects (Bezard et al.

2015; Horstkotte et al. 2022). For this reason, animals preferentially choose peatlands in summer and semi-arid and arid mountain birch forests in early and late summer (Bezard et al. 2015).
A change in these living arrangements occurred in the 1880s. Reindeer herding from that time on was carried out by separate reindeer herding cooperatives, which introduced a pasture rotation system separating winter and summer pastures by fences (Kumpula et al. 2011). This practice has continued in the study area up to the present day.

The strongly glacially influenced landscape of the study area in Kaamanen (Inari) shows corresponding characteristics such as eskers and moraines, which are responsible for the relief in the valley areas between the mountain ranges (Derbyshire und Owen 2018). Elevations vary from 185 to 370 m above sea level (Paoli et al. 2018). The terrain became ice-free about 9000 years ago, but the former glaciation is still evident today when looking at the soil, among other features (Derbyshire und Owen 2018). Mainly sandy sediments and gravel deposits can be found in the soil as typical glacial remains, while fine materials such as silt and loess were washed out and removed by aeolian processes after the glacial melt (Derbyshire und Owen 2018).
Lakes and peat mires with graminoids and shrub vegetation intersperse the pine (*Pinus sylvestris*) and mountain birch (*Betula pubescens ssp. czerepanovii*) forests that predominate in the area. The understory vegetation is primarily composed of evergreen dwarf shrubs e.g., hermaphrodite crowberries (*Empetrum nigrum ssp. hermaphroditum*), lingonberries (*Vaccinium vitis-idaea*), common heather (*Calluna vulgaris*), and twinflowers (*Linnaea borealis*) (Oksanen und Virtanen 1995; Maliniemi et al. 2018). The most common graminoid species is *Deschampsia flexuosa* (wavy hair-grass), but deciduous dwarf shrubs such as the European blueberry (*Vaccinium myrtillus*) and the dwarf birch (*Betula nana)* also occur more frequently in the area. Red-stemmed feathermosses (bryophytes, e.g. *Pleurozium schreberi*) and fork mosses (*Dicranum spp.*) as well as soil lichens like reindeer lichen (*Cladonia rangiferina*), shrubby cup lichen (*Cladonia arbuscula*), and other *Cladonia* lichens (*Cladonia spp.*) are typical for the ground layer (Oksanen und Virtanen 1995). The vegetation assessment undertaken during the sampling in Inari actually revealed four main vegetation types at the sampling sites: Mixed forest, mainly consisting of *Pinus sylvestris* and B*etula pubescens ssp. czerepanovii* at sites E-1M-A, S-2M, W-3M, W-4M-A and -B, W-5M and MR (with differences in understory vegetation), wet birch forest, mainly consisting of *B. czerepanovii* and with a ground layer holding *Vaccinium* and *Sphagnum spp.* underneath at sites S-5F, W-4P and FR, non-forested areas consisting of a tundra-like mixture of heath and grassland vegetation, mainly covered with *Salix sp.*, *Vaccinium sp.* and *Empetrum nigrum* at sites S-2P, S-3M, S-3P, W-3P, S-4P, and PR, and grasslands without a significant shrub layer and with very few species that occurred only at the grazing-intensive sites S-5P , W-5P-A and -B, and S-5M (Windirsch et al. 2023).

The study area is characterized by a typical subarctic and continental climate. January is the coldest month with a mean air temperature of -13.1 °C, while July records the warmest temperature with a mean of 13.9 °C. From 2008 to 2020, the mean annual air temperature was 0.1 °C (monthly observation data from the weather station in Inari Kaamanen (Finnish Meteorological Institute 2021)). The month of July is characterized not only by the highest temperatures, but also by the highest precipitation (69.2 mm). Based on monthly averages, the annual precipitation totals 458.4 mm (Finnish Meteorological Institute 2021).

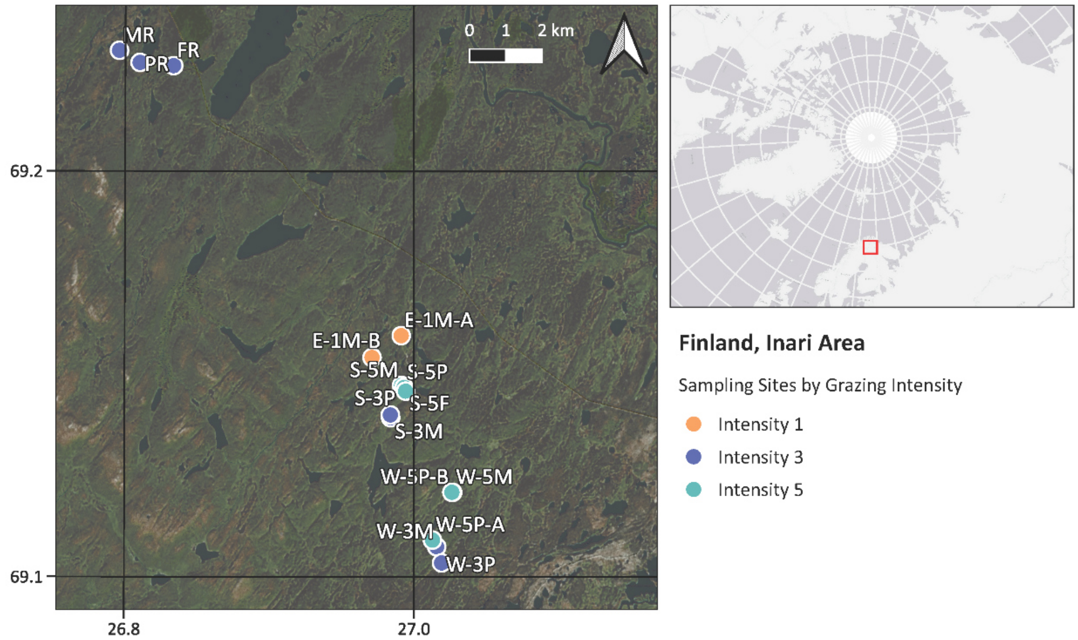

*Figure 3: **Study Area in Finland, Inari**. The figure shows the location of the study area in a circumpolar map, marked by the red square, as well as the location of the sampling sites with intensity 1 sites in orange, intensity 3 sites in blue, and intensity 5 sites in green. The map was created using the free geographic information system software QGis. The basemaps were provided by ESRI.*

Figure 3 shows the study area in Kaamanen and the location of the 15 examined study sites. Individual sampling locations are labeled. Of these, 12 were located in the area of the Kutuharju field research station and three in the reindeer summer pastures of the Muotkatunturi Cooperative (Windirsch et al. 2023). Considering these two areas individually, some special characteristics should be noted. The Kutuharju field research station, characterized by peatlands (16.9 %, 7.5 km²) and mineral soil deposits (77.0 %, 34.4 km²), has a total area of 44.6 km², with lakes accounting for about 4.6 % (2.1 km²) and rocky terrain without ground cover accounting for about 1.5 % (0.7 km²) of the total area (coverage based on the National Land Survey of Finland 2021 (Windirsch et al. 2023)). After the autumn slaughter, the animals count about 170-200 individuals, resulting in an average reindeer density of 4.4 reindeer/km² (Finnish Reindeer Herders' Association 2022). Divided into four fenced areas, the site provides a defined habitat for each season of the year (early summer, all summer, late summer, winter). In comparison, the territory of the Muotkatunturi Reindeer Herding Cooperative (surrounding areas outside the fences) has an expanse of 2580 km². With a maximum reindeer population of 6800 animals, the reindeer density here is 2.6 animals per km² (Finnish Reindeer Herders' Association 2022).

2.2 Field Work

For the field work of the Chersky and Inari pilot studies to which this thesis refers, sampling sites were selected based on grazing intensity, meaning the intensity of herbivore activity (Windirsch et al. 2022; Windirsch et al. 2023). Therefore, any reference to "grazing" in the following thesis implies all animal activities, since trampling, defecation, and browsing always occur where animals graze. The grazing intensities were detected through long-term observations of animal preferences, as well as on multi-day observations which preceded the start of the field campaigns in Siberia and Finland. Since a long-term experiment under controlled conditions, meaning long-term observation and sampling of un-grazed sites under a gradual introduction of herbivores, was not possible due to limited field time, a space-for-time approach was taken for both study areas (Windirsch et al. 2022; Windirsch et al. 2023).
A space-for time approach provides a method for studying processes of slow ecological change by assuming an equivalence of temporal and spatial variation (Pickett 1989). Under such an approach, relationships between ecological variables are examined at sites that are assumed to be at different stages of development, while initially being identical (Walker et al. 2010). For this approach, seemingly similar sites within the same landscape units, ideally differing only in grazing intensity, were selected (Windirsch et al. 2022; Windirsch et al. 2023). A prioritization of the investigated number of herbivore treatments and landscape positions over the number of replicates within a given treatment and site made an analysis of a larger range of site conditions possible. Furthermore, the approach aimed for a detailed overview over a large area, which could be provided by sampling a high number of individual sites (Windirsch et al. 2022; Windirsch et al. 2023).
Originally, a comparison of the Finland and Siberia samples was not intended. The sites were not selected for possible comparability of the study areas. Consequently, a direct comparison must be considered with caution. Nevertheless, answering the question raised in this thesis for both areas individually and thus as examples for permafrost and seasonally frozen soil, is suggestive to detect a possible difference between those soil types, that could, if differences do occur, be further investigated. Due to similar procedures of the field and laboratory work, a separate description of the methods was refrained from.

The nomenclature scheme of samples and study sites for Chersky and Finland differed and was adjusted for better comparability. For Chersky, a nomenclature scheme was adopted that provided information on both landscape type, that is (i.e.), thermokarst basin (B) or Yedoma uplands (U), and grazing intensity, i.e., intensive grazing (3), occasional grazing (2), and no grazing (1) (Windirsch et al. 2022). The nomenclature scheme of Inari is more comprehensive. Three categories of grazing intensity

could be identified, namely control sites without herbivore occurrence, sites along the reindeer migration routes, and sites in the reindeer pastures (Windirsch et al. 2023). Reindeer migration routes are sites used by reindeer for passage and thus experience occasional grazing pressure, while the sites in the reindeer pastures are affected by long term grazing and trampling. However, based on the previous long-term observations, 5 intensities of herbivore activity could be identified within these 3 upper categories: no grazing (1), occasional migration route (2), daily migration route (3), high-frequency daily migration route (4) and pasture or supplementary feeding site (5). Apart from the intensity, the site and sample labels also indicate other relevant characteristics. Thus, the letters M stand for mineral soil, P for peat, and F for forest. Although core samples of the forest sites were mainly peat soils, a differentiation based on tree cover appeared necessary. The summer sites at the Kutuharju station were additionally labeled with the letter S, while the winter sites show a W in the label. Reference areas outside the station are indexed by an R and exclosure sites by an E (Windirsch et al. 2023).
In order to be able to compare the results of Chersky and Inari intensity-related, the nomenclature of the Chersky samples was adjusted. Samples of the original intensity 2 were relabeled to intensity 3 and samples of the original intensity 3 to intensity 5.

To cover the different site characteristics noted in the Chersky nomenclature scheme, 5 sites were selected for the Siberian study area (Windirsch et al. 2022). One soil core was sampled per site, resulting in a total of 5 cores. Of these, B5 was an intensively grazed site in a wet area of the thermokarst basin. Site B3 differentiated itself by extensive grazing and its location near the Pleistocene Park fence. In contrast, site B1, which was not grazed, was located outside the park. U5 and U1 were sites on a Yedoma upland. The latter was also located outside the park fence and was thus ungrazed, while U5 was intensively grazed by herbivores. In this context, the terms "intensive grazing" and "occasional grazing" are to be understood as relative. "Intensive" refers to a daily presence of grazing animals for several hours while "occasional" refers to an infrequent presence of animals where feeding is conducted alongside animal tracks. Animals do not have access to the area outside the park (Windirsch et al. 2022).
With the goal of selecting sites with similar characteristics, thereby making animal influence the main variable and minimizing differences between all other variables, sampling sites were selected by placing the three B sites in the same drained thermokarst basin and the two U sites on the same Yedoma upland complex (Windirsch et al. 2022). Unfortunately, experimental deforestation was undertaken at site B1 in 2015. The environmental difference that this unavoidably caused, may have affected the soil characteristics at the site. In this regard, soil compression of the active layer due to the use of heavy mowing machines should be considered in particular. Another uncontrollable difference between sites appeared to be the flooding regime (seasonal or occasional). In this regard, an effect on the soil is

likely. Because there are no separate summer and winter pastures at Chersky, each site is exposed to the same grazing pressure year-round (Windirsch et al. 2022).

In Inari, originally 18 sites were selected to cover all 5 intensities and different site characteristics (Windirsch et al. 2023). If multiple vegetation types were present within a grazing intensity, each type was tested. In addition, other locations outside the research station were sampled. Visually, these matched the locations of migration routes within the station site and were assigned an intensity classification of 3. These locations were considered to represent the natural grazing condition, with "natural" referring to the usual grazing intensity associated with reindeer herding in Fennoscandia throughout history (Windirsch et al. 2023). This resulted in a total of 21 sample cores for the study area in Finland, of which 15 were considered in this study. For an overview of the core samples and their characterizations, see Appendix A.

Initially, in both Siberia and Finland, a visual record of the environment and of the main vegetation types was made at each site. This was done by identifying the predominant species and their average height in the field, and in some cases retrospectively using photographs (Windirsch et al. 2022; Windirsch et al. 2023). For this purpose, plots of 1 x 1 m were established, in whose center soil samples were subsequently taken in the form of a soil core or a soil profile. In Inari, the plots were selected with the deliberate exclusion of trees from their surface, since tree roots would make soil sampling difficult. Nevertheless, it was taken into account if trees were present in a surrounding area of about 10 x 10 meters in order to make an appropriate classification (forest or open land). Based on the plots, the dominant vegetation types were estimated. As part of this identification, only the most predominant species were recorded in order to note the main differences between the sites (Windirsch et al. 2022; Windirsch et al. 2023).

Due to the different soil characteristics, it was necessary to use different instruments and methods for taking the cores and soil profiles in Finland and Siberia. For Finland, it is further important to note the different sampling procedures for peat and mineral soils. At peat sites, it was attempted to record not only the entire peat layer but also the first few centimeters of the underlying mineral soil (Windirsch et al. 2023). When selecting the sampling sites, it was ensured that neither hilltops nor steep slopes or valley bottoms were chosen, so that disturbing factors such as soil erosion and differences in soil moisture would be avoided. Sites with ponding water or dried-up vegetation were also avoided to maintain site comparability. Peat cores were collected using a Russian peat corer (Eijkelkamp) with 50 cm sample length and a volume of 530 cm^3. Winter sites were sampled in June 2022, while summer and reference sites were sampled in September 2020. While peat cores in the field were sampled in 5 cm increments, at mineral soil sites samples were extracted according to all visible soil horizons. At these sites, soil profiles were excavated and sampled using fixed volume cylinders. Both the fixed volume cylinder and the peat sampler allowed determining the volume of each subsample, which made a subsequent calculation of bulk density possible. The samples from Inari were stored in Whirlpak sampling bags and kept cool during transport (Windirsch et al. 2023).

To sample the soil in Chersky, the active layer was removed with a spade down to the permafrost (Windirsch et al. 2022). After measuring the thaw depth, the soil profile was sampled using steel cylinders with a volume of 250 cm^3. At the intensively grazed site B5, the soil was saturated from the surface to the frozen ground (38 cm), which made cylinder sampling impossible. Alternatively, blocks of 8 to 10 cm in height were cut from the soil profile with a knife. The organic top layer for all sites was sampled separately. For the permafrost layer, a permafrost drill from the Snow Ice and Permafrost Research Establishment (SIPRE) with an inner diameter of 7.6 cm was used. This allowed sampling of both the still frozen parts of the active layer and the underlying permafrost. The SIPRE drill provided a maximum sampling depth of 110 cm below surface (bs) at B5, 108 cm bs at B3 and 127 cm bs at B1, as well as 114 cm bs at U5. During the summer field campaign, it was not possible to sample Site U1 due to the tall and dense shrub vegetation and the resulting inaccessibility. Instead, sampling took place the following winter. The SIPRE drill was able to sample the site to a depth of 72 cm bs, with the site being completely frozen at the time of extraction. After taking the soil samples, the cores were individually packaged in sterile plastic bags and transported on to the laboratories in a frozen state (Windirsch et al. 2022).

In the vicinity of sample site S-2M in Inari as well as sample site U5 in Chersky, additional fecal samples (reindeer in Inari, horse in Chersky) were collected for mercury reference values (Windirsch et al. 2022; Windirsch et al. 2023). At site U5 this was supplemented by fur (reindeer) and vegetation sampling (Windirsch et al. 2022).

2.2 Laboratory Analysis

To determine the possible influence of herbivores on the mercury content in Arctic soils, this parameter had to be determined for all samples. For this purpose, the samples were first freeze-dried by a Zirbus Sublimator 15 (Windirsch et al. 2022; Windirsch et al. 2023). The frozen Chersky cores were previously cut into approximately 5 cm long samples in the laboratory according to the stratigraphy using a band saw. In order to provide other parameters, such as the bulk density (BD), determined with the help of the sample weight after freeze-drying and the sample volume, as well as the ice or water content, determined by the weight before and after drying, a corresponding mass determination (using Mettler Toledo KERN FCB 8K0.1, accuracy ± 0.1 g) was carried out before and after the use of the Zirbus Sublimator. Subsequently, all subsamples intended for biogeochemical analysis were grinded in a planetary mill (Fritsch Pulverisette 5). This was done using agate cups for the soil samples and corundum cups for organic samples (fur, dung and vegetation) (Windirsch et al. 2022; Windirsch et al. 2023).

With the grinded and homogenized samples, the elemental analysis could be carried out. For this purpose, 50 milligrams (mg) of material was weighed into tin capsules or steel crucibles, depending on the analysis. For mercury, the determination was carried out using a Direct Mercury Analyzer (Milestone Slr DMA-80). Since for a few samples the mercury content was so low that the minimum measuring range of the instrument was not reached, the measurements for these samples were repeated with a sample weight of 200 mg.

Other parameters, such as BD and absolute water content (AWC), had already been measured for the original pilot studies (Windirsch et al. 2022; Windirsch et al. 2023). A number of these will also be consulted in this thesis in order to discuss possible correlations. These include total organic carbon (TOC), which, like total carbon (TC), was determined by pyrolysis using an elemental soliTOC cube, as well as total nitrogen (TN) that, also by combustion analysis, was determined by using an Elementar rapidMAX N for the Inari samples and a vario EL III for the Chersky samples. TOC and TN were then used to calculate the carbon-to-nitrogen ratio (TOC/TN). TOC/TN ratios could not be calculated for samples with TN or TOC below the detection limit of 0.1 percentage by weight (wt%). Particle size distribution was measured for all mineral soil samples using a laser particle sizer (Malvern Panalytical MasterSizer 3000), after previously removing organic material from the samples by adding hydrogen peroxide. The grain size distribution was intended to allow verification of similarities between the sediment substrates. A measurement of the peat samples, on the other hand, was impossible due to a lack of mineral material (Windirsch et al. 2022; Windirsch et al. 2023).

Other parameters such as the stable carbon isotope ratio (δ13C) of the TOC content as well as the age of the samples are not discussed in the following and can be neglected at this point. Furthermore, the results of the lipid biomarker analysis performed on the alcohol fraction and the n-alkane fraction is not relevant to this thesis, and thus a further description of the associated methods will not be provided.

2.3 Data Analysis

For the data analysis of the sample series, the statistical program R (version 4.2.3) was used. Since in Inari the sites of intensity 2 and 4 formed an intermediate or transitional category and a clear assignment was not always possible, the decision was made to remove the associated values from the data set. In addition, since Chersky distinguishes only three categories, this measure creates a better comparability of the sample sets. This resulted in 80 Chersky samples (excluding the reference samples) and 187 Finland samples (excluding the reference sample) for the data analysis. One dung sample, belonging to an intensity 2 site, was retained as a general reference size. Cores of the same intensity and soil type were combined in the data analysis. In addition, an overall data set was created that included both the Chersky and Inari samples to provide an overall view of Arctic soils in general. The total data set contains values of 267 samples (excluding the reference samples). Especially in Chersky the grazing intensity has been artificially changed during the last decades (Windirsch et al. 2022), which is why the strongest differences were expected in the seasonally thawing layer, as it can show changes of recent periods. For a separate consideration of near-surface soil layers, another reduced dataset was created to represent only the upper 20 cm of the samples.

As part of the data analysis, statistical parameters (mean, median, maximum, minimum and standard deviation) were calculated for the different soil types (permafrost, seasonally frozen peat soils, and seasonally frozen mineral soils) as well as for the different grazing intensities. For illustration purposes, associated boxplots were created using the program Grapher (version 11). Furthermore, the visualization through scatter plots was used to illustrate the depth development of the mercury values of different cores and intensities as well as to show a general distribution of the mercury values for different intensities.

In addition, Pearson correlation tests were performed in the R environment using the 'corrr' package to reveal possible links between mercury levels and other variables. These included mean depth, intensity, soil type, TOC content, mean grain size (MGS), AWC and seasonality.

3 RESULTS

3.1 TOC Concentrations, Absolute Water Content and Mean Grain Size

In order to consider other variables possibly influencing mercury content in the soil, apart from grazing intensity, the results of TOC, AWC and MGS were included in the analysis and will be presented in the following.

The TOC content in samples of Chersky's permafrost soil shows a mean value of 9.20 wt% and ranges from 0.79 wt% (CH19-B1 35.25 cm bs) to 52.8 wt% (CH19-B1 92.5 cm bs) throughout all sites (Windirsch et al. 2022). Therefore, they have overall lower values than Finland's seasonally frozen soils. These show a mean of 35.01 wt% and range from 0.19 wt% (FI20-MR 32 cm bs) to 55.08 wt% (FI20-S-3P 67.5 cm bs) (Windirsch et al. 2023).

Looking at the AWC in the permafrost samples, a mean value of 43.47 wt% is recorded, with values ranging from 15.59 wt% (CH19-U5 87.5 cm bs) to 85.74 wt% (CH19-B1 112.5 cm bs) (Windirsch et al. 2022). Consequently, the samples from Chersky show lower values than the seasonally frozen soils as well. These have a mean value of 69.75 wt% and range from 7.53 wt% (FI20-E-1M-A 36.5 cm bs) to 93.19 wt% (FI22-W-P5-B 5 cm bs) (Windirsch et al. 2023).

The mean grain size could not be determined for peat samples from Inari, due to the absence of mineral material. The results of Chersky with a mean of 10.14 micrometer (µm) and values ranging from 4.56 µm (CH19-B5 20.25 cm bs) to 20.15 µm (CH19-U5 103.5 cm bs) show the smaller values for this variable (Windirsch et al. 2022). Although the samples of the seasonally frozen soil have a mean of 118.77 µm, range from 29.85 µm (FI22-W-5P-A 132.5 cm bs) to 335.10 µm (FI20-S-5F 109 cm bs) and therefore show higher values, it must be mentioned that only 39 of 187 samples were measurable for this parameter in total (Windirsch et al. 2023).

Individual sample values for TOC, AWC and MGS can be found in Appendix B.

3.2 Mercury Concentrations

The results of mercury measurements on samples from the Chersky and Inari sites are initially considered separately. The Finnish peat and mineral sites are additionally separated due to their different soil properties. It should be noted that when a distinction is made between mineral and peat soils in the following, an allocation and categorization was made per core and therefore per site and not for individual sample points within the core. The decision was made based on the predominant soil type at the study site.

3.2.1 Mercury Concentrations in Chersky's Permafrost Soils

The sites on permafrost ground in Chersky show a mean total mercury (THg) content of 38.87 microgram/kilogram (µg/kg) (see Table 1). The maximum (Max) measured value is 101.57 µg/kg while the minimum (Min) value equals 5.38 µg/kg. The value for the standard deviation (SD) already indicates that a site and intensity comparison is of importance.

Table 1: Statistical parameters for the Chersky data set. *The vegetation, dung, and fur samples were not included in the calculations.*

Value	THg [µg/kg]
Mean	38.87
Median	33.38
Min	5.38
Max	101.57
Standard Deviation	19.12

Also, the depth mercury trends of the different cores should be considered. As Figure 4 shows, intensity 3 has the highest average values when comparing intensities. However, if only the active layer (separation by colored line corresponding to the core) is considered, intensity 5 shows the highest values, which are visibly lower in the permafrost layer. In addition, the intensity 5 cores show greater irregularities in the active layer than the others.

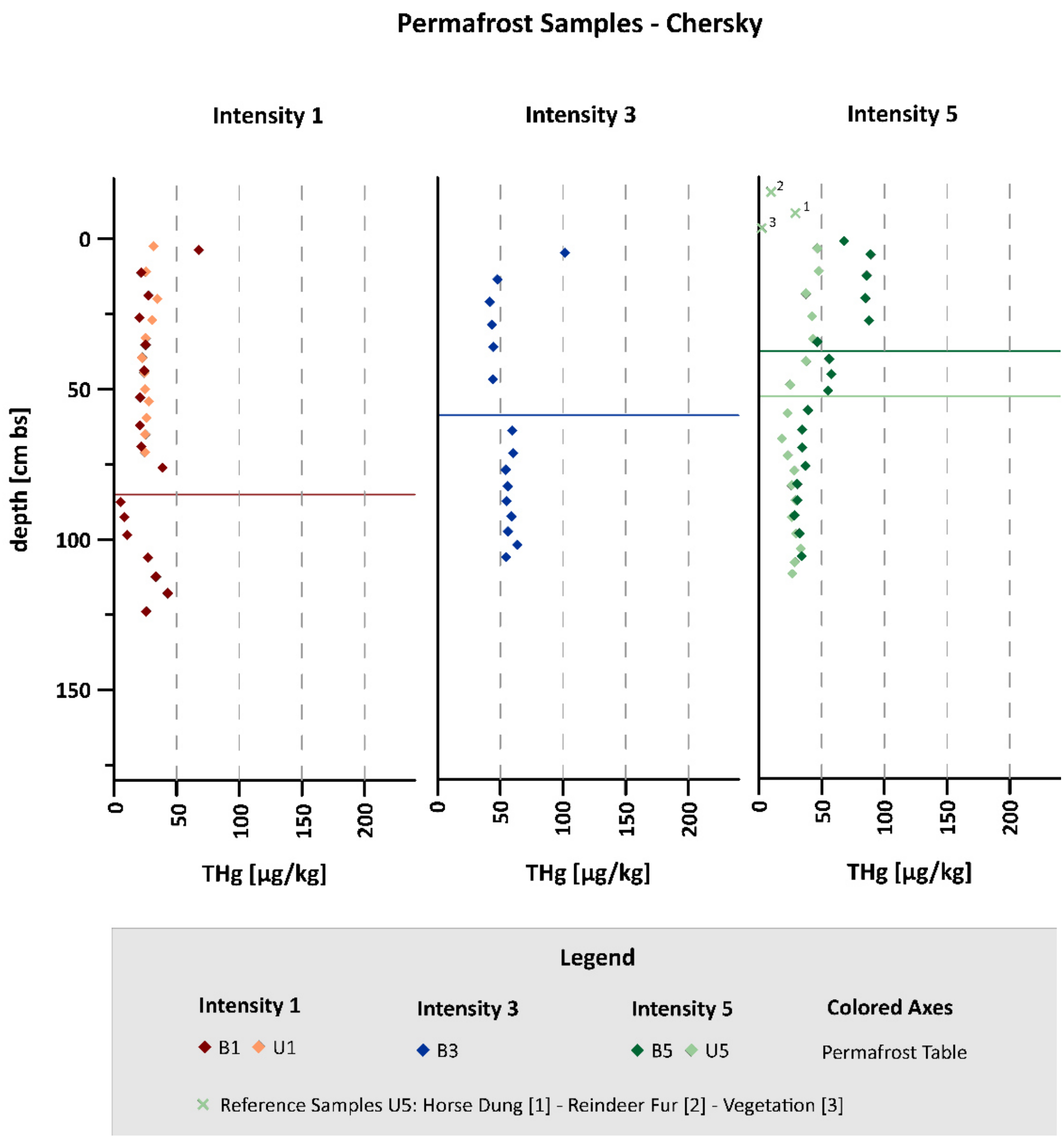

*Figure 4: **Depth plots for the permafrost samples of Siberia, Chersky**. The different grazing intensities are illustrated by using shades of orange for intensity 1, shades of blue for intensity 3, and shades of green for intensity 5. The rhombuses symbolize year-round grazing. The permafrost tables of the different cores are shown in the corresponding color.*

No clear differences are visible between thermokarst basin and Yedoma upland sites. In the active layer, the mercury content of the Yedoma samples is slightly higher at intensity 1 and slightly lower at intensity 5. However, the number of cores (5 in total) does not seem sufficient for a comparison between thermokarst basins and Yedoma upland.

The permafrost table can be easily recognized by the mercury values and their depth development. This is especially true for core B1, where the values in the frozen layer start very low (5.38 µg/kg, which is considerably lower than the last value of the active layer) and then increase distinctly. It should be noted that the uppermost 5 samples below the permafrost table of B1 are located in a peat layer, while all other samples from Chersky consist of mineral soil. Mercury levels within this peat layer appear to be particularly low, while the underlying mineral soil sample point shows a noticeably higher concentration (42.93 µg/kg). Nevertheless, the increasing trend in the permafrost layer must not be ignored.

The only exception is the value of the deepest sample, which again shows a lower mercury concentration (25.69 µg/kg at 124 cm bs). The active layer of this core shows hardly any variation in its mercury levels. Only the first (67.77 µg/kg) and the last value (38.75 µg/kg) are higher than the rest, ranging constantly between approximately 20 and 25 µg/kg. In contrast to B1, U1 was completely frozen. The values hardly vary with depth and are very similar to those of the active layer of B1.
For intensity 3, the particularly high value of 101.57 µg/kg at the top of the active layer is noteworthy. The rest of the active layer shows nearly identical values between 41.56 and 47.67 µg/kg. The same applies to the permafrost layer. However, the concentrations here are a little higher than those of the active layer (between 54.62 and 63.34 µg/kg) and thereby indicating the position of the permafrost table.
Core B5 shows an outlier with otherwise similar mercury concentrations in the active layer. The deepest sample point of the unfrozen layer has a lower concentration than the rest. In contrast, the values in the permafrost layer show no conformity. Instead, minor fluctuations are observable. Contrary to the results of intensity 1 and 3, a decline in mercury content with depth is visible. Nevertheless, fluctuations and decreases are only small. Accordingly, this should not be considered an actual trend. Compared to the active layer, the values below the permafrost table are noticeably lower. While the average mercury content of the active layer, excluding the outlier, is 83.06 µg/kg, it amounts to only 39.14 µg/kg for the permafrost layer. In general, this core shows an unusual pattern in the depth profile.
Under a first examination of core U5 in Figure 4, it seems like rather unsteady values occur in the active layer with an almost wavelike depth development (increasing - decreasing - increasing - decreasing). In fact, the values range between 24.96 µg/kg and 47.69 µg/kg with an average of 39.97 µg/kg and are therefore quite similar. The permafrost layer shows a similar picture of conformity with values ranging from 18.32 µg/kg to 33.28 µg/kg and an average of 26.57 µg/kg. They hardly increase with depth.

Further information on the Chersky cores can be found in Table 2, and individual sample mercury contents are reported in Appendix B.

*Table 2: **Results of the individual cores of active and permafrost layer giving the sample count, Δ depth, Δ THg, and mean THg of the Chersky sample set.** The vegetation, dung, and fur samples were not included in the calculations. A separation into active layer and permafrost layer was not possible for core B1 due to the time of sampling. Accordingly, the data is not available (NA).*

Core	**B1**	**U1**	**B3**	**B5**	**U5**
Sample Count	17	12	15	18	18
Δ Depth [cm]	127	72	108	110	114
Δ THg [µg/kg]	62.39	12.09	59.9	60.64	29.37
Mean THg [µg/kg]	26.05	26.92	56.03	51.75	31.78
Sample Count Active Layer	10	NA	6	6	7
Δ Depth Active Layer [cm]	80	NA	59	38	53
Δ THg Active Layer [µg/kg]	46.33	NA	59.9	42.33	22.73
Mean THg Active Layer [µg/kg]	28.92	NA	53.74	76.98	39.97
Sample Count Permafrost Layer	7	NA	9	12	11
Δ Depth Permafrost Layer [cm]	42	NA	49	72	61
Δ THg Permafrost Layer [µg/kg]	37.55	NA	9.08	27.71	14.96
Mean THg Permafrost Layer [µg/kg]	21.95	NA	57.56	39.13	26.57

3.2.2 Mercury Concentrations in Finland's Seasonally Frozen Mineral Soils

*Table 3: **Statistical parameters for the mineral soil samples of the Inari data set.** The dung sample was not included in the calculations.*

Value	**THg [µg/kg]**
Mean	41.31
Median	23.06
Min	1.48
Max	232.68
Standard Deviation	52.80

The sites of Finland's seasonal frozen ground (SFG) consisting of mineral soils show a mean mercury content of 41.31 µg/kg (see Table 3). The maximum measured value is 232.68 µg/kg while the minimum value equals 1.48 µg/kg. Additionally, the maximum of the seasonally frozen mineral samples is the highest mercury content measured in all sample sets examined for this thesis. Especially the standard deviation shows that a site and intensity comparison is highly relevant. In Figure 5, the depth trend of the various cores is illustrated. The sample series from Finland has 7 mineral cores, from which only 30 subsamples could be obtained. For this reason, statements on intensity comparison and depth development are difficult. A difference between the various grazing intensities is not noticeable when looking at Figure 5.

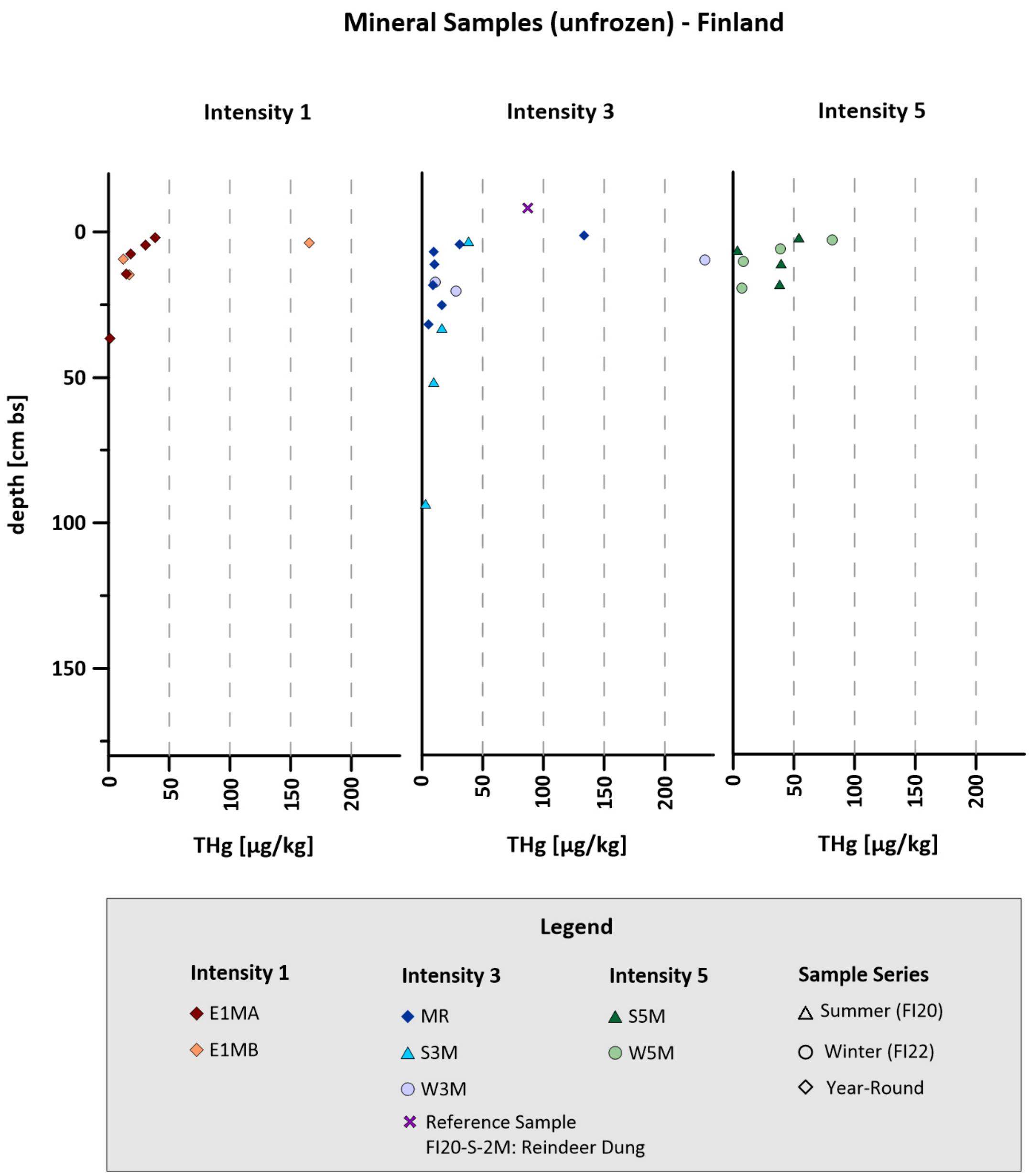

Figure 5: Depth plots for the mineral soil samples of Finland, Inari. *The different grazing intensities are illustrated by using shades of orange for intensity 1, shades of blue for intensity 3 and shades of green for intensity 5. The circles symbolize winter grazing sites, squares summer grazing sites and rhombuses year-round grazing.*

With only three sample points, a statement about the depth trend at site E-1M-B is not possible. Nevertheless, a particularly high value of this core near the surface is noticeable (165.45 µg/kg at 3.75 cm bs). For E-1M-A, a clear decrease in mercury content with depth can be observed, starting with the near-surface value of 38.46 µg/kg to the last value at 36.5 cm bs with a concentration of 1.48 µg/kg.

The MR results are a special case in terms of the site. Mercury content behaves quite erratically with depth. Starting with two high values, one exceptionally high (133.6 µg/kg) and one slightly higher value (31.01 µg/kg), the four samples beneath are in very low ranges with a slight upward trend. The last value drops again distinctly (5.65 µg/kg).

The mercury content of core S-3M decreases almost linearly with depth, starting with the near-surface value of 93.66 µg/kg to the last value at 38.5 cm bs depth with a concentration of 3.54 µg/kg.
At the W-3M site, too few and too closely spaced sample points are available to make a statement about the depth trend. Nevertheless, an extremely high value is found here as well, which stands out remarkably from the overall picture. It is the highest measured value of all cores of all sites (232.68 µg/kg).
The two cores of intensity 5 (S-5M and W-5M) behave relatively similarly. For both, mercury levels decrease with depth. However, for S-5M, there is one value that abruptly shows a lower mercury content than the other sample points. This value equals only 3.64 µg/kg while the average mercury content of the remaining three values of this core is 43.96 µg/kg.
At both intensity 1 and intensity 5 sites, the sample points are quite close to each other. No great depth is reached, which makes a reliable statement about the depth development difficult.
Concerning the comparison of summer and winter sites, no clear difference can be seen. However, in two out of three cases the winter sites show strong outliers and hardly detectable depth trends, while in the reindeer summer ranges the values mostly decrease.

The site of the dung sample was removed from the dataset examined in this study. Accordingly, since its grazing intensity (intensity 2) was not analyzed, the value was added to the plot of intensity 3 (see Figure 5). As a reference sample, it is addressed further in Chapter 3.2.4.

Further information on Finland's seasonally frozen mineral cores can be found in Table 4 and individual sample mercury contents in Appendix B.

Table 4: Results of the individual mineral soil cores giving the sample count, Δ depth, Δ THg, and mean THg of the Inari sample set. *The dung sample was not included in the calculations.*

Core	**E-1M-A**	**E-1M-B**	**MR**	**S-3M**	**W-3M**	**S-5M**	**W-5M**
Sample Count	5	3	7	4	3	4	4
Δ Depth [cm]	40	17.5	35	42	22	22	22.5
Δ THg [µg/kg]	36.98	153.46	127.95	90.12	201.58	50.38	74.49
Mean THg [µg/kg]	20.68	64.77	30.89	45.56	90.38	33.88	34.13

3.2.3 Mercury Concentrations in Finland's Seasonally Frozen Peat Soils

Table 5: Statistical parameters for the peat soil samples of the Inari data set

Value	THg [µg/kg]
Mean	50.20
Median	41.56
Min	0.22
Max	205.74
Standard Deviation	33.70

The sites of Finland's seasonally frozen peat soils show a mean mercury content of 50.20 µg/kg (see Table 5). The maximum measured value is 205.74 µg/kg while the smallest concentration equals 0.22 µg/kg. The minimum represents the smallest measured value within all the sample series studied.
Again, the standard deviation indicates the need to look at different cores and intensities individually. Figure 6 shows the depth trend of the various cores.

The sample series from Finland has no peat core for intensity 1. While the mercury content of FR decreases with depth, showing only one outlier, PR behaves slightly wavelike, though overall with a decreasing trend. The outlier from site PR is the closest value to the surface at 93.96 µg/kg. The value from the neighboring sample is higher, showing a concentration of over 200 µg/kg.
Core S-3P, on the other hand, behaves in a strongly undulating and irregular pattern. Nevertheless, an overall decreasing trend can be identified here as well, with the upper sample point showing a value of 38,2 µg/kg, therefore actually belonging to the smaller values of this core, and the lowest sample point showing a value close to zero.
For core W-3P, there are only a few sample values available at depths that are not widely spaced. Looking at the few values available, one can see a decreasing trend in mercury over depth, starting with the near-surface value of 104.79 µg/kg to the last value at 22.5 cm bs with a concentration of 71.4 µg/kg.

The cores of intensity 5 show extremely strong fluctuations and irregularities. The only core that is relatively consistent in mercury levels is core W-5P-B. Here the values are very similar and clearly higher than the values of the rest of the cores for the sites of seasonally frozen peat soils, only similar to site FR.
For S-5F, S-5P, and W-5P-A, no regularities or trends are apparent. Values are a little higher in the upper samples and lower in the deeper samples here as well. Nevertheless, the two sample points closest to the surface of core W-5P-A are noteworthy for their mercury content, which is clearly lower than those immediately following.
A clear difference between summer and winter sites is not detectable.

Further information on Finland's seasonally frozen peat cores can be found in Table 6 and individual sample mercury contents in Appendix B

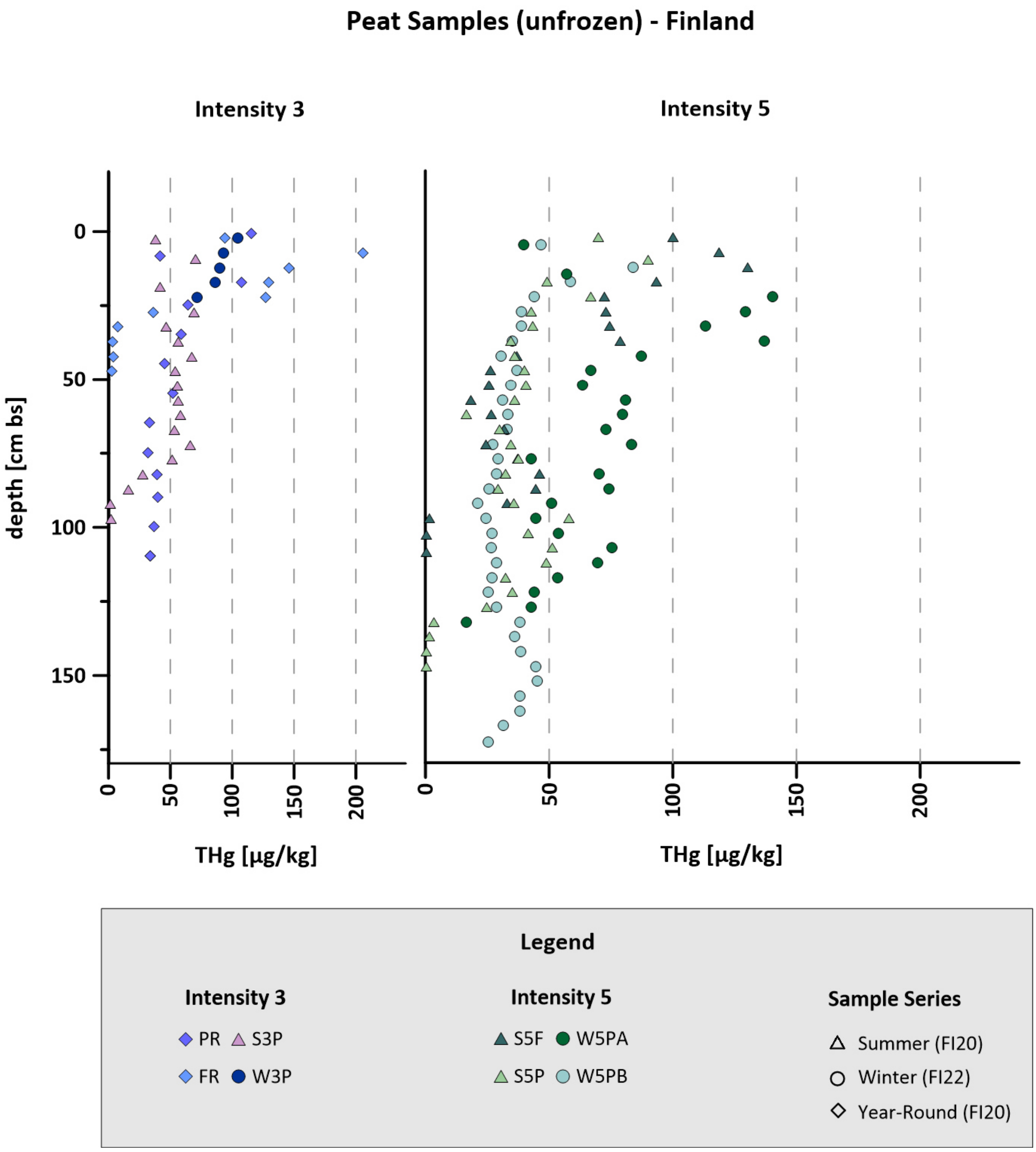

Figure 6: Depth plots for the peat soil samples of Finland, Inari. *The different grazing intensities are illustrated by using shades of blue for intensity 3 and shades of green for intensity 5. The circles symbolize winter grazing sites, squares summer grazing sites and rhombuses year-round grazing. To improve the visualization and clarity of the intensity 5 plot, the X-axis has been modified and was scaled differently.*

Table 6: Results of the individual peat soil cores giving the sample count, Δ depth, Δ THg, and mean THg of the Inari sample set.

Core	PR	FR	S-3P	W-3P	S-5F	S-5P	W-5P-A	W-5P-B
Sample Count	14	10	18	5	22	29	25	34
Δ Depth [cm]	125	50	100	25	112	150	135	176
Δ THg [µg/kg]	114.38	202.90	68.65	33.39	129.89	88.87	128.5	62.91
Mean THg [µg/kg]	50.16	75.52	46.25	88.94	49.79	36.65	71.57	35.30

3.2.4 Reference Values

As shown in Table 7, the mercury content measured in the vegetation is comparably small. Fur and dung (horse) from Chersky also show rather low mercury levels. In contrast, the dung sample (reindeer) from Finland is strikingly high. The site not further investigated in this thesis shows considerably lower values in the examination of its soil samples. Even when compared to the rest of the mercury content in Inari, the dung value seems remarkably high.

Table 7: Mercury concentration of the reference samples (vegetation, fur, dung)

Sample Type	Sample Site	THg [µg/kg]
Vegetation	CH19-U5	2.25
Fur	CH19-U5	9.70
Dung	CH19-U5	28.99
Dung	FI20-S-2M	87.24

3.3 Correlation Test Results

A Pearson correlation test of the variables mercury, depth, intensity, soil type, TOC, AWC, MGS and seasonality was performed with a significance level of 0.05. The results are shown in the form of a correlation matrix in Figure 7. Non-significant results are indicated by a cross. It should be emphasized that these results only refer to correlations and not necessarily to causalities.

The calculations showed a negative correlation for the variables depth and mercury with a correlation (cor) value of -0.37 and a p-value of 4.88^{-10}. This indicates that the greater the depth of the soil sample is, the higher the mercury concentration will be. In contrast, no significant correlation was found for the variables mercury and intensity (p-value = 0.20). While both soil type (cor-value = 0.25; p-value = 3.67^{-5}) and TOC (cor-value = 0.41; p-value = 2.72^{-12}) correlate positively with mercury, meaning that the more peaty the material and the higher the TOC content is, the higher the mercury concentration will be, a negative correlation was calculated for the variables MGS and mercury. A cor-value of -0.58 and a p-value of 1.44^{-11} was recorded here. Accordingly, the mercury concentration seems to increase the smaller the grain size is. Both AWC (cor-value = 0.44; p-value = 5.44^{-14}) and seasonality (cor-value = 0.13; p-value = 3.20^{-2}) show a positive correlation with mercury. This indicates that mercury concentration increases with rising AWC. It also shows that the mercury concentration is highest at sites with grazing in winter and lowest at sites with grazing all year round.

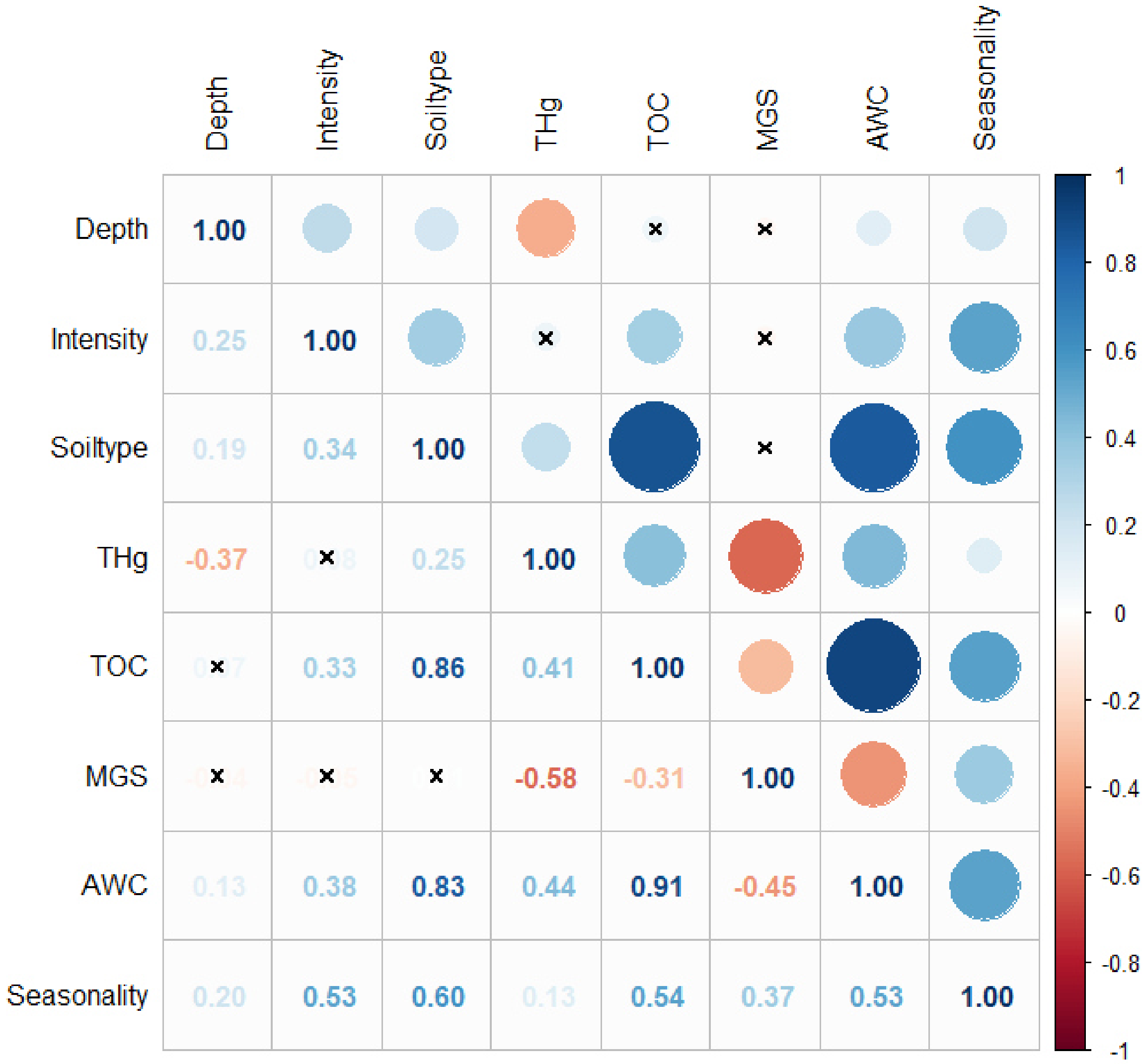

Figure 7: Correlation matrix of the merged data set. *The figure above shows the results of the Pearson's correlation test for a merged data set of the Siberian and Finnish samples. Negative correlations are illustrated in red and positive correlations in blue. Non-significant correlations are crossed out.*

The values from Table 8 indicate that there is no depth trend for TOC as well as for MGS. Water content, on the other hand, correlates positively with depth. TOC and AWC also correlate positively with intensity, while MGS shows no significant correlation with this variable.

Table 8: Results of the correlation test for non-mercury-interactions

Value	**Depth-TOC**	**Depth-AWC**	**Depth-MGS**	**Int.-TOC**	**Int.-AWC**	**Int.-MGS**
cor-value	-	0.13	-	0.33	0.38	-
p-value	2.66e-1	3.75e-2	6.39e-1	2.90e-8	1.89e-10	6.13e-1

4 DISCUSSION

In the following sub-chapters the effect of large herbivores on the mercury concentration in Arctic soils will be discussed. In order to get an impression of the extent of the actual mercury contamination in the study areas beforehand, a comparison with measured mercury levels of other studies will be made, independent of grazing. A study that examined mercury levels in Alaskan permafrost measured an average of 43 ± 30 µg/kg THg (Schuster et al. 2018). Soil layers of the upper 2.5 m were sampled, making them comparable to the values in this study in terms of depth. Another study focused on Hg concentrations of various deposits in the deep permafrost of Siberia (up to 36 m bs) (Rutkowski et al. 2021). There, THg concentrations ranged from 0.86 to 34.52 µg/kg with a mean value of 9.72 ± 9.28 µg/kg. In this setting, only a few subsamples were collected from a similar depth as Schuster et al., so a direct comparison would be insufficient. The sediment layers closest to the surface showed concentrations of 17.64 ± 10.40 µg/kg (subsamples from the uppermost 3.5 m) (Rutkowski et al. 2021). In permafrost peatlands in the Stordalen area (northern Sweden), mercury levels of 55 ± 11 µg/kg were found in near-surface peat cores (Rydberg et al. 2010).

Overall, the measured mercury concentrations are similar to those determined for this study, where the total data set showed a mean and standard error of the mean (SEM) of 45.81 ± 2.04 µg/kg, the Chersky data set showed a mean of 38.87 ± 2.14 µg/kg, and the Inari data set showed a mean of 48.78 ± 2.73 µg/kg.

Different values were found for a critical limit of mercury in soils. A study from 2015 suggested a value of 0.36 mg/kg (36000 µg/kg) Hg in soils as a critical concentration above which plants and soil organisms will be affected (Soares et al. 2015). However, the focus of this study was on tropical soils. Another limit is proposed by Tipping et al. who used data from toxicity experiments to derive a critical limit for soil that should protect 95% of species (plants, invertebrates, and microbes). From this he derived a value of 0.13 µg/g (13000 µg/kg) (Tipping et al. 2010). Although measured mercury concentrations in the Arctic are below these limits, their relevance should not be underestimated, especially when considering the increasing trend of mercury deposition in the Arctic. Whether grazing by large herbivores shows a positive effect on the fixation of mercury in the soil is now discussed below.

4.1 Impacts of Herbivores on Soil Mercury Concentration

4.1.1 Development of Mercury Concentration with increasing Soil Depth

Incorporating the knowledge that herbivores have a cooling effect on Arctic soils during winter (Windirsch et al. 2022; Holmgren et al. 2023), it was hypothesized that animal presence and activity should have an effect on soil mercury levels as well, because more effective cooling could slow or even halt microbial decomposition, allowing harmful mercury to remain fixed in the soil for a longer time period. For the depth trend of the pollutant, it was presumed that a stable condition of similar values or possibly even an increasing trend of mercury concentrations with depth would be revealed for the permafrost layer at sites with herbivore activity. The assumption is based on the premise that the permanently frozen soil layer is protected by the soil cooling effect of the animals, and mercury cannot be transported or washed out under frozen conditions. More fluctuation was expected in the active layer, where the effects of inputs, outputs and transport could be apparent, and the upper soil layers could represent the effects of the contemporary introduction of herbivores (Windirsch et al. Under Review). Similar considerations were made for the seasonally frozen soils in Finland. Although no permanently frozen ground provides stable conditions here, an increasing trend of mercury with depth was not completely ruled out. This was reasoned by the consideration of herbivores providing colder and probably even frozen top soil conditions for a longer time in winter, and thus fixing mercury accumulated at depths for a longer period of time. However, the consideration of an increasing trend with depth excludes the soil layers near the surface, which are directly exposed to mercury input and where correspondingly high values were expected. For sites without herbivore activity, higher fluctuations and irregularities were presumed in depth development than for sites with herbivore activity, due to lack of stabilizing conditions and stronger influence of local environmental factors.

Most results from the Chersky sample series showed clearly identifiable permafrost tables in mercury concentrations. This was especially true for site B1 with no herbivore activity. Here, the clearly increasing trend in the permafrost layer was striking, starting with a particularly small value that suddenly decreased compared to the active layer. An explanation for this can probably be found in the present soil type. The first 5 sample points of the permafrost layer consist of peat, while the samples below are mineral soil. It is likely that a transport of material to deeper depths is diverted to the horizontal due to the frozen conditions, insulated by the peat layer, and potential other lateral fluxes above the permafrost table. The relatively high value observed at this location appears to confirm the occurrence of mercury accumulation above the permafrost table. The increasing values in the permafrost layer suggest that deep accumulation originally occurred here as well, but input from the active layer was reduced at a certain point in time. Contrary to the assumption that the active layer will show more fluctuations, the upper soil layer of site B1 shows even more stable values than the permafrost layer. The fact that the first value is comparatively high can be explained by mercury input on the surface. Despite deforestation in 2015, no anomalies are observed with regard to mercury distribution at site B1, suggesting that this disturbance did not have a major impact on soil mercury concentrations.

In contrast to B1, U1 was completely frozen. However, this is related to the time of sampling. The samples show comparatively steady values, hinting to a stable environment in general, even without herbivore activity.

Although B1 forms a particularly clear example, permafrost tables are also quite evident at the other sites. This can be seen by either slightly decreasing or increasing jumps in mercury concentration in otherwise consistent values. The general differences in mercury levels between permafrost and the active layer could be explained by site-related inputs and outputs that do not affect the permafrost layer because of its frozen state and, as long as no deeper thawing occurs, leave the existing permafrost unaffected.

As expected, the permafrost cores show stable conditions with hardly fluctuating mercury levels. Only the core of site B5 shows slight irregularities in direct comparison to the rest. However, these are only minor and possibly caused by input or material differences during deposition. An increase with depth, on the other hand, can be assumed for site B5, but not determined with certainty. A clear trend of this kind is only evident at core B1, i.e., at a site without herbivore influence. This depth development is therefore presumably related to pre-existing factors.

Also noteworthy are some particularly high mercury concentrations near the surface, as already addressed while discussing B1. It seems reasonable to attribute these high levels to surface influences. Various potential sources of surface inputs and aggregations of mercury need to be addressed in this regard. Most notably, atmospherically carried mercury is of importance, when considering that atmospheric Hg deposition in the Arctic increased profoundly in comparison to pre-industrial background levels (Enrico et al. 2017).

In elemental form, mercury occurs on Earth in rock inclusions (Gworek et al. 2020). Considerable amounts are also found in the bound form of cinnabar (mercury sulfide). Volcanoes and geothermal springs are natural sources of this heavy metal (Gworek et al. 2020), which is removed from its deposits and released into the environment primarily through human influence (Clemens 2013).

In the context of anthropogenic influences, however, mercury emissions that result from the combustion of fossil fuels play a particularly important role (Clemens 2013). Mercury is thus released in its elemental state into the atmosphere, where it has an approximate residence time of 6 to 18 months and is distributed over large areas by wind (Gworek et al. 2020).

Since elemental mercury is poorly soluble in water (CARPI 1997) and due to its relatively low melting and boiling points (Gworek et al. 2020) it tends to remain in the gas phase (Clemens 2013). However, sooner or later, mercury can be oxidized by reactive atmospheric gasses and becomes highly water soluble from that point on. Captured by aerosols, it is washed out of the atmosphere by rain and carried into soils and water bodies (Gworek et al. 2020; CARPI 1997).

When mercury is carried into the sea, it is converted by microorganisms into methylmercury (MeHg), a biologically active and highly toxic compound (Morel et al. 1998). MeHg accumulates through the food chain and can even produce adverse health effects in fish and fish consumers, including humans (Morel et al. 1998; Chiang et al. 2021). Because methylmercury is a major pollutant in aquatic environments (Lehnherr 2014), it can be assumed that it also plays a role in near-water terrestrial systems such as wetlands, where occasional or regular flooding occurs. In this context, it is important to consider that the thawing of permafrost in the Arctic leads to the formation of small thermokarst lakes, ponds and wetlands (Gordon et al. 2016; Olefeldt et al. 2016). Due to the high input of organic matter and nutrients as well as their microbial activity, they likewise provide favorable conditions for MeHg production (MacMillan et al. 2015; Gordon et al. 2016; Roth et al. 2021) and potentially become a source of MeHg to nearby rivers when runoff occurs (Fortier et al. 2007).

In this study, some of the sites are exposed to flooding. This affects the thermokarst basin permafrost sites in Chersky, especially site B5. Looking at the depth profile of mercury levels, the high near-surface values of the active layer are most likely the result of input from flooding. However, it was not possible to differentiate between elemental mercury, MeHg or other mercury compounds.

Another important source of mercury input is vegetation. Mercury is taken up by plants, together with CO_2, directly from the air through their stomata (Clemens 2013). Plants incorporate the pollutant, even though it has no biological function for them (Clemens 2013). Through leaf fall in autumn or general plant death and decay, the mercury returns to soil and water (Gworek et al. 2020).

Evidently, herbivores play an important role in this context. By consuming vegetation, mercury enters the animal cycle, is excreted in concentrated form, and then released back into the soil (Hejna et al. 2019; Gfeller et al. 2021). In fact, the study by Gfeller et al. indicates that soils with a high manure input show a fast sequestration of Hg and a higher percentage of Hg bound by particulate organic matter (Gfeller et al. 2021), implying that the mercury in animal dung has a relevant influence on the soil mercury content.

Although there was no possibility to measure the atmospheric mercury content at the study sites, reference samples were collected to get a better sense of potential mercury concentrations in the environment, and hence input to the soil. Dung samples were collected in both research areas and showed rather distinct differences in their levels. The reindeer dung sample from Finland was noticeably higher than the soil sample collected at the same site. This could indicate a high mercury input in the area around Inari, which is potentially returned to the soil in concentrated form via the animals. The comparison to the mercury content of the associated soil sample was made because the dung sample, due to a concentrated amount of Hg, could affect the soil mercury content. If the concentration of the dung sample is clearly higher than that of the soil samples at the corresponding site, the Hg content in the soil will increase substantially when the dung is incorporated into the soil. The greater the difference between dung Hg and soil Hg, the more pronounced this will be. Thus, the dung-Hg concentration could be used to indicate the extent of the effect of mercury concentration by animals on the soil. Comparing the mercury content of the dung sample in Inari (87.24 µg/kg) and the associated soil

samples (mean Hg content: 16.17 µg/kg), it can be concluded that the reindeer might have a high effect on soil mercury concentration through dung input.
The horse dung sample from Chersky had only about one-third of the mercury content of the Finnish dung sample. Though soil-mercury concentrations in Chersky are also affected by herbivore excretions, this influence is likely less intensive than in Finland.
In Chersky, in addition to the dung sample, reindeer fur from the previous winter, and on-site vegetation were collected and measured for reference values as well. Fur is a common biomarker of mercury exposure in the environment (Eccles et al. 2019). In addition, established relationships exist between total mercury in fur and organs. The reindeer fur studied had a mercury content of 9.7 µg/kg. Looking at comparative values from a study of mercury in the fur of Alaskan caribou (*Rangifer tarandus*), where an average value of 55.3 µg/kg THg was measured in free-living animals (Duffy et al. 2005), the value found in the Siberian reindeer fur sample is comparably small. Similarly, the Siberian vegetation sample has only a low value, in comparison with values from a study in Alaska, where about 30 to 60 µg/kg was measured for bulk vegetation, depending on location and type (Olson et al. 2019).
The low values in Siberia suggest that mercury input to the soil might be mainly from flooding and rain, while in Finland the effect of mercury concentration through herbivore excretion is more pronounced. However, it must be pointed out that these reference values originate from single samples and for this reason cannot be considered representative. Nevertheless, the high mercury concentrations of the upper soil samples indicate higher inputs from the surface. This applies to both Siberia and Finland.
As expected, the cores from Finland, especially the peat cores, show larger fluctuations in their depth trend, which are likely caused by deposition or could possibly be explained by fluctuating input quantities and active mercury transport within the soil.
Furthermore, decreasing mercury levels with increasing depth have been observed. This trend appears to be evident for both peat and mineral soil cores, although only a few and closely spaced sample points were available for the latter. The outstanding value of core S-5M (7 cm bs) of 3.64 µg/kg is likely a result of the small soil horizon depth. The visible slight difference between winter and summer sites for the mineral cores, in which winter sites show strong outliers and barely recognizable depth trends in two out of three cases while the values on reindeer summer pastures mostly decrease with depth, are likely caused by other factors such as spatial heterogeneity of the source material, local vegetation assemblages or similar.
For the seasonally frozen soils of Finland, no clear difference can be seen between the depth developments of the cores.
Considering the depth trend, mainly found in the Finland samples, an accumulation of mercury at depth, favored by the soil cooling effect induced by the reindeer, can consequently not be claimed. Therefore, the decrease with depth must be caused by decreasing surface influence.

Due to the short time span between the introduction of grazing and sampling (23 years for permafrost areas, 50 years for areas with seasonally frozen ground), it can be assumed that a possible effect of herbivores would be mainly visible in the upper soil layers, as more contemporary events can be reflected here (Windirsch et al. Under Review). For this reason, it is advisable to take a look at the top 20 cm of soil.
To check whether the top 20 cm behave differently from the rest of the soil layers, separate correlation tests were performed for the corresponding sample points. Only slightly higher correlation values could be identified, which is plausible considering the proximity to the surface. Considering Figure 5 and 6 no significant differences in depth trends can be found either, if we disregard the already discussed circumstance that very near-surface samples often show higher mercury concentrations. Apart from core W-5P-A, which is extremely variable, there is a general trend of decreasing mercury concentrations with depth, as seen when considering the overall data set. Specifics of the Active Layer of permafrost samples are discussed further in Section 4.2.

Another potential effect that, due to its not directly mercury related aspect, has not been addressed so far and that could occur as a result of herbivore-induced soil cooling is the protection and stabilization of the permafrost table. Because permafrost is threatened by climate change and the loss of permanently frozen soils through thawing is already an ongoing process (Hinzman et al. 2005; Smith et al. 2010), any potential way to stabilize this soil type is highly relevant. According to the assumptions made so far, the active layer above the permafrost table should be thickest at sites with no animal influence, since it can be assumed that the permafrost thaws faster there due to the lack of additional soil cooling, and thus the depth of the active layer increases. The soil depth of the permafrost table would steadily shift downward. At intensity 5 sites, on the other hand, the permafrost should still be furthest intact and thus closer to the surface. Since directed grazing has not been occurring on the study plots for very long, an effect of this type might not yet have been observable due to the insufficient time elapsed. However, a look at the location of the permafrost tables in Figure 4 shows the expected differences between the intensities quite clearly. Specifically, the permafrost table of intensity 1 is located at a depth of 85 cm bs (B1), for intensity 3 at a depth of 64 cm bs (B2), and for intensity 5 at depths of 59 cm bs (U5) and 38 cm bs (B5). This shows that even after the short duration of grazing, a positive effect can already be observed. However, in order to confirm whether this is due to the animals, the shifting of the permafrost tables at the study sites would have to be observed as part of a long-term study.

4.1.2 Comparison of Sites with different Herbivory Intensity

Comparison of soils exposed to different grazing intensities is key for testing the hypothesis that herbivore activity has an effect on mercury levels in Arctic soils. It was assumed that higher mercury concentrations occur at sites with more intense herbivore activity compared to exclosure sites, because the soil-cooling effect of the animals should lead to mercury fixation in the soil more effectively and for longer time periods. Fixation of mercury would inhibit further transport as well as a possible washout or release back to the environment, and instead allow for mercury accumulation in the soil. A positive correlation between mercury content and intensity was expected, meaning that with an increase in herbivore activity, a higher mercury content should occur.

However, grazing intensity is not the only factor that could have an influence on mercury concentration. In order to get an overall picture of possible factors influencing mercury levels and to avoid possible fallacies based on the sole consideration of intensity as the only impacting aspect, it is necessary to discuss the results of the correlation matrix in Figure 7 in its entirety. It should also be noted that the correlation matrix represents the results of a merged overall data set, including both Chersky and Inari, and thus permafrost and seasonally frozen ground results.

As discussed in the previous chapter, a negative depth trend in mercury concentration is observed for most of the cores from Finland. This is also shown by the correlation analysis for these two variables resulting in a significant correlation value of -0.37. Since for the samples from Chersky comparatively constant values with depth were observed, the Finnish samples seem to have the higher influence on the calculations due to their higher total number. For the consideration of Arctic soils in general, this is not relevant at this point. However, since obvious differences between the study areas have already been observed, the hypothesis is tested for Chersky and Inari, as well as for the Finnish peat and mineral soils individually in Chapter 4.2. This will also allow for a comparison of permafrost and seasonally frozen ground. Nevertheless, a discussion of the overall results seems reasonable due to the heterogeneity of Arctic grounds on the circumpolar scale and will be continued in the following.

Mercury content and soil type show a positive correlation with a correlation value of 0.25. The soil types were translated into a numeral code for the purpose of correlation testing, assigning the number 1 to mineral soil and the number 2 to peat soil. Accordingly, the result of the correlation test shows that the mercury content in peat soils is significantly higher than in mineral soils. This can be explained by the fact that the organic material of peat soil takes up and fixates mercury (Schuster et al. 2018), and can therefore store mercury better than mineral soil. This also explains the high positive correlation of TOC and mercury (0.41), because mercury is bound to organic matter (OM), indicated by high TOC.

Another high positive correlation is found when considering the variables of AWC and mercury (0.44). Assuming water mechanically washes out mercury and transports it, the result seems contradictory at first. Theoretically, water could collect and accumulate the mercury. For this to be confirmed, the mercury would have to increase with depth, which can not be seen in the results. Also, since the study areas are relatively flat, the correlation value cannot be explained by relief. However, with a higher water content, a higher TOC content is also found (correlation value = 0.91). Since OM stores water, with soil-OM being able to hold up to 1.0 times its weight in available water on average (Libohova et al. 2018), and OM also binds mercury (Schuster et al. 2018), the positive correlation of absolute water content and mercury is plausible, even though the two parameters are not affecting each other directly, making it a spurious correlation.

The grain size correlates negatively with the mercury content with a value of -0.58. This is another predictable result; the smaller the grain size, the denser the soil, the better substances such as mercury are trapped and stored in the soil (Maslennikova et al. 2012). The only exception would be if the density of the soil is so high that substances cannot infiltrate and are carried away horizontally by other fluxes. An example for this can be found at the permafrost tables, which are extremely dense due to their frozen state. Especially under consideration of the core B1 in Figure 4 the mercury content indicates that substances are redirected to the horizontal.

The variable of seasonality, i.e. the annual time when the animals are present on each site, also shows a significant, though weak, positive correlation with a correlation value of 0.18. Seasonality was also given numbers for the correlation analysis, with number 0 assigned to year-round accessibility of the site. Summer sites were assigned number 1 and winter sites were assigned number 2. Accordingly, the correlation value shows that mercury levels are highest at sites with grazing in winter and lowest with year-round grazing. Conforming to the assumption that herbivore activity leads to soil cooling and consequently to a better storage of mercury, one would assume that year-round grazing would be most effective, since continuous grazing should result in a stronger transformation of vegetation in summer, along with snow compaction in winter, thus a higher cooling effect and consequently also a continuously effective storage of mercury in the soil can be expected. However, the result of the correlation test shows the opposite. The sites categorized as year-round grazing intensity unluckily feature a) all non-grazed sites in intensity 1, and b) an unequal number of sites per grazing intensity (intensity 1: 4 sites; intensity 3: 4 sites; intensity 5: 2 sites). Thus, herbivore density across all year-round sites appears comparatively small and would explain the correlation trend. That mercury levels are higher in the winter area than in the summer seems plausible, since the important "extra" cooling of the soil by animal-induced compaction of the snowpack occurs in winter, which ensures that less of the frozen soil thaws in the summer and thus more mercury is stored rather than transported.

In order to provide a complete discussion of the correlation test results, the variables not directly tested for correlation with mercury must also be briefly reviewed.

It was noted in Chapter 3.3 that there was no trend with depth for both TOC and MGS. This is due to the fact that peat and mineral samples are considered as a combined sample set. For the peat samples, which are superior in number and therefore have a greater influence on the result of the correlation test, a high amount of TOC is present due to the OM, regardless of depth. The MGS is not defined for

the peat samples, which due to the distribution of peat and mineral samples, cannot lead to a significant correlation. This also explains why MGS has no significant correlation with intensity.
On the other hand, the fact that water content correlates positively with depth could indicate that water accumulates in deeper soil layers at some sites. However, it should be noted that with a correlation value of 0.13, this is only a weak connection. TOC and AWC both correlate positively with intensity. The correlation of grazing on carbon storage in permafrost soil in northeastern Siberia and in seasonally frozen soil in northern Finland was investigated by Windirsch et al. for the present sampling points separated by study area as part of the pilot studies mentioned earlier (Windirsch et al. 2022; Windirsch et al. 2023). For Finland, it was found that there was no significant difference between grazing intensities in terms of TOC content, but that TOC content depended mainly on soil TOC content before the introduction of intensive herbivory. For Chersky, on the other hand, intensive grazing was found to result in a more stable soil thermal regime and thus higher carbon storage in the thermokarst deposits and active layer. The fact that TOC and intensity showed a positive correlation when the two study areas were combined is most likely explainable by the correlation of TOC with AWC, which has already been discussed earlier.
The correlation of AWC and intensity, on the other hand, raises the possibility that the animals prefer to stay at sites with high water content, which would be plausible in view of its effect on vegetation and therefore forage as well as drinking water availability.
Having discussed all possible influencing factors, it can be summarized that the OM content and therefore the TOC content seem to have an important influence on the mercury concentration due to their adsorbing properties. This again demonstrates the relevance of the separate consideration of mineral and peat soil, which will be addressed in the next chapter. Initially, however, the potential impact of different herbivore activity on Arctic soils will be discussed under consideration of the total data set.
A look at the correlation matrix in Figure 7 shows, contrary to expectations, no increase in mercury content with increasing grazing intensity. With a p value of 0.20, the correlation test did not produce a significant result. Thus, in the overall consideration of the merged data sets, herbivores do not appear to have an effect on soil mercury levels.

This is also shown by the scatter plot in Figure 8. In case of a confirmed hypothesis, the mercury content, here plotted versus depth, should have shown clusters. However, this is not the case.

Likewise, no trend is evident from the values in Table 9.

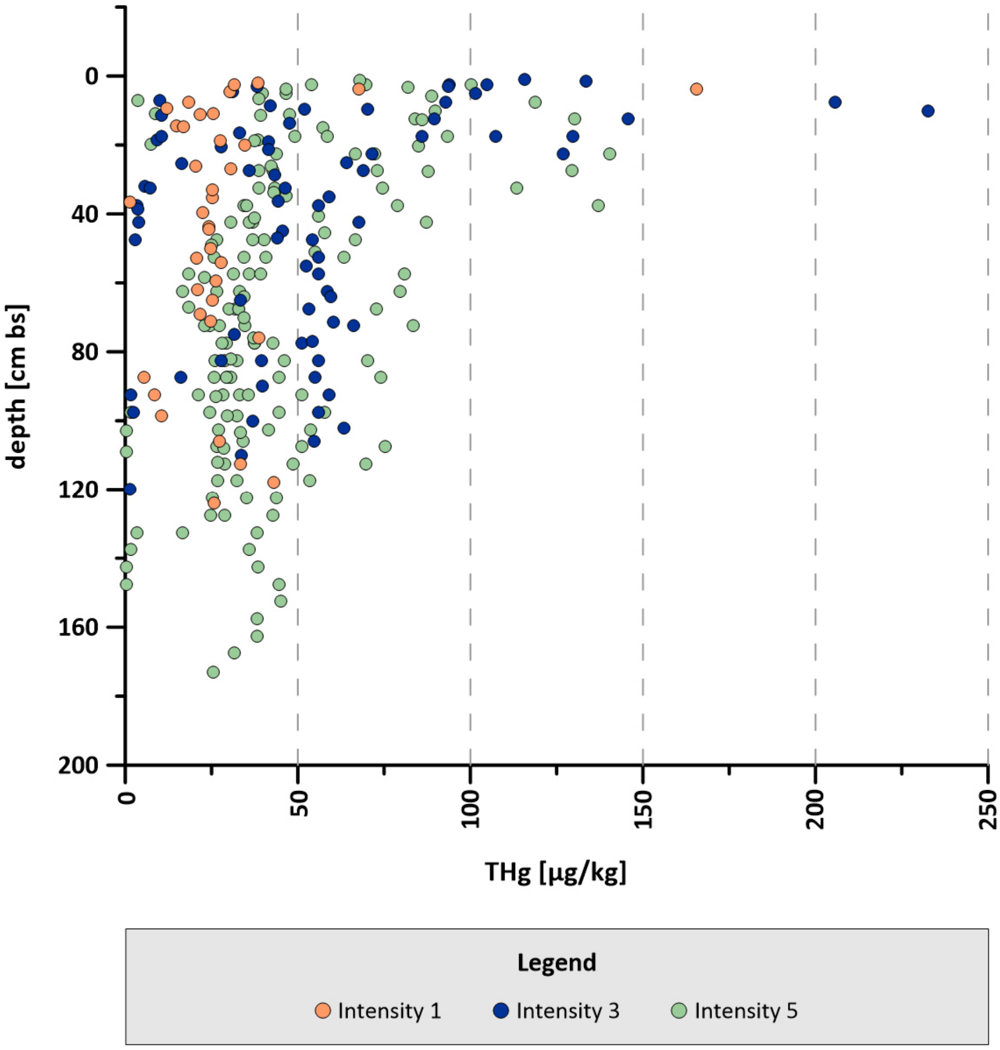

Figure 8: Scatter plot of mercury concentrations for a merged data set. The figure above plots mercury levels versus depth. The distinction of the different intensities does not reveal any clusters.

Table 9: Comparison of mercury-related statistical values for different grazing intensities in a merged data set.

Value [µg/kg]	Intensity 1 (37 Samples)	Intensity 3 (76 Samples)	Intensity 5 (154 Samples)
Mean	28.75	55.85	44.95
Median	25.12	52.10	37.83
Min	1.48	1.29	0.22
Max	165.45	232.68	140.40
SD	25.77	43.19	27.06

The fact that the hypothesis could not be confirmed in this context could have several reasons. First, it is possible that the number of animals is simply insufficient to lead to an environmental change large enough to cause soil cooling intense enough for an accumulation and fixation of mercury in the soil. However, as noted in the description of the sites in chapter 2.1, this is not true at least for the Pleistocene Park at Chersky, where vegetation has already visibly changed with animal activity (Pleistocene Park Foundation 2023). Including the melting (-38.84 °C) and boiling (356.58 °C) points of mercury (Hofmann 1918; Zhang et al. 2011), mobilization and onward transport in frozen soil can also be ruled out. However, since all samples from Finland are thawed at least throughout summer, there is a possibility that an effect of animals is only evident in the more stable conditions of permafrost. Seasonal thaw might result in too much variability due to input and transport, which could fade any potential effect of herbivore activity. Permafrost and seasonally frozen soils, as well as the layers above and below the permafrost table and Finland's mineral and peat soils, should be subject to individual examinations, which is discussed in the following chapter 4.2.

It is also possible that the space-for-time approach is not sufficient for reflecting animal effects due to small-scale spatial variability of the soil. A more suitable approach might be the long-term monitoring and sampling of ungrazed areas under gradual introduction of herbivores, which might lead to different results. However, a long-term study of this kind was not possible due to complicated site access and remoteness of the study areas. Also, while such an approach would provide a good baseline of ungrazed sites, natural development of ungrazed sites over time would not be present in the resulting data set.

Nevertheless, the eventuality that herbivore activity simply may not have a sufficient effect on soil to result in mercury fixation and accumulation cannot be ruled out.

4.2 Mercury Concentration in different Soil Types from different Arctic Study Areas

Due to the differences found between the Chersky and Inari sample series and the strong correlation between mercury concentration and organic matter content, the different soil types are discussed separately and are then compared.

The data in Table 10 shows the lowest mean mercury content for permafrost ground at intensity 1 and at intensity 5 for the mineral samples of seasonal frozen ground. Intensity 3 sites show the highest mean concentrations for all soil types. However, it is noticeable that intensity 5 sites show lower values than intensity 3 sites, while the mean value of intensity 5 of Finnish mineral soils (34.00 µg/kg) is even lower than that for sites without grazing (37.21 µg/kg).

Table 10: Comparison of mercury-related statistical values for different soil types and grazing intensities

SOIL TYPE	Permafrost			SFG MINERAL			SFG PEAT	
INTENSITY	1	3	5	1	3	5	3	5
Mean [µg/kg]	26.41	56.03	41.77	37.21	47.83	34.00	58.18	46.80
Median [µg/kg]	25.24	54.97	34.38	17.57	22.05	38.60	53.27	38.40
Min THg [µg/kg]	5.38	41.56	18.32	1.48	3.54	3.64	1.29	0.22
Max THg [µg/kg]	67.77	101.57	88.89	165.45	232.68	81.82	205.74	140.40
SD [µg/kg]	11.17	14.38	19.48	53.02	65.03	26.81	41.92	29.05

The difference between ungrazed areas (intensity 1) and grazed areas of intensity 3, is most obvious for permafrost with a difference in mean values of 29.62 µg/kg. For comparison, this value equals -10.62 µg/kg for Finnish mineral samples of the seasonally frozen soil. The value cannot be determined for the peat samples due to missing data points for intensity 1.

It is important to point out that the Finnish mineral samples of intensity 3 only show a higher mean than those of intensity 1 because of the outlier of 232,68 µg/kg. Without it, the mean of intensity 3 would only reach 33.61 µg/kg and thus be slightly lower than that of intensity 1, which would contradict the expectations. However, a possible explanation can be found by considering the vegetation. Due to the exclusion of herbivores at intensity 1 sites in Finland, ground-covering and therefore isolating species such as *Cladonia rangiferina*, which has been observed at this site (Windirsch et al. 2023), are able to grow stably and undisturbed. Such a layer of vegetation not only insulates the soil from low winter temperatures, but unlike graminoid vegetation, also insulates the soil from summer heat (Block et al. 2010). The summer shading effect, as well as generally lower soil temperature amplitudes, could thus compensate for the absence of the positive effect of large mammal herbivory on soil and mercury storage. However, this explanation, based on vegetation, can only apply to areas where herbivores can be excluded and where environmental characteristics also allow the growth of this type of vegetation. Using this explanatory approach, it can now be argued that at the site of grazing intensity 3, the influence of animals is too strong to form an isolating lichen layer. Yet, at the same time, it would be too weak to cause animal-induced vegetation shifts toward graminoid-dominated vegetation and to cause effective soil cooling by snow trampling. Under this consideration a lower mercury value at intensity 3 than at intensity 1 sites seems plausible.

That the intensity 5 mean for the mineral samples of seasonal frozen ground is even lower than that of intensity 3 was influenced by some particularly low concentrations at intensity 5 sites and sporadic particularly high concentrations at intensity 3 sites. A look at the distribution of the values with the help of the boxplots in Figure 9 is useful here.

Nonetheless, it must be mentioned that an intensity comparison splitting the soil types is not entirely unproblematic. Inari's mineral samples have only a small number of sampling sites. For intensity 1 of the peat soil, on the other hand, there are no values at all, which makes a direct comparison of sites with and without grazing impossible.

Especially considering the boxplot in Figure 9, it is important to keep the number of sample values in mind. Due to large differences in this aspect, the results are not ideally comparable. With a larger and more uniform sampling, the boxplots would potentially look different.

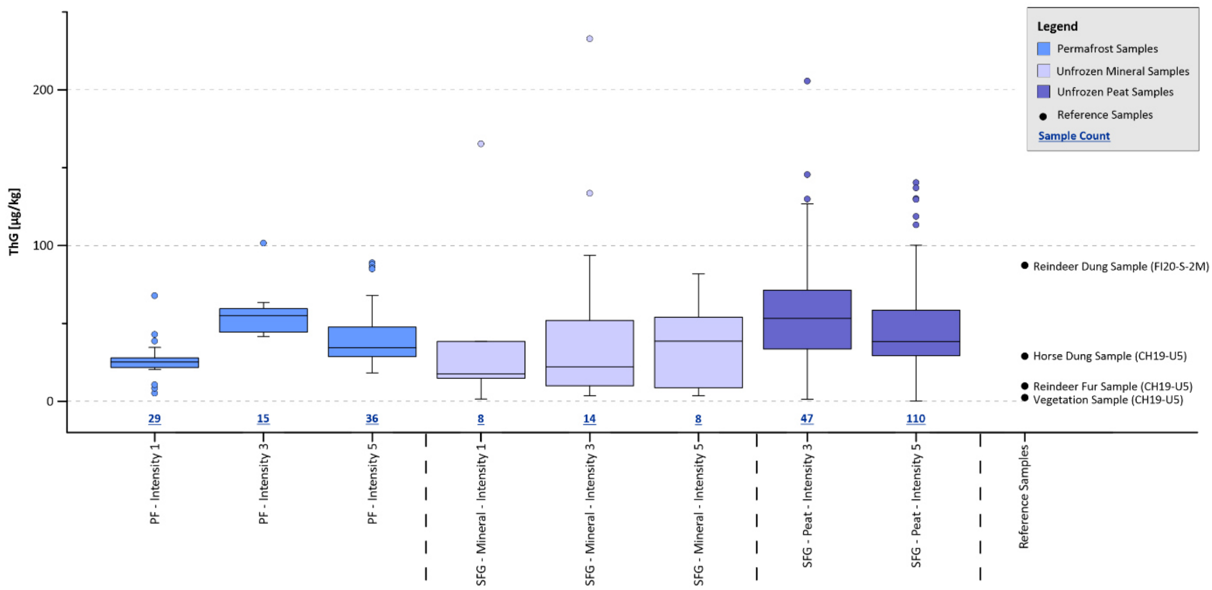

Figure 9: Boxplots of mercury concentrations for different soil types and grazing intensities

Generally, it is visible that the peat cores of the Finland sample set have the highest mercury values. Intensity 3 has higher values on average than intensity 5, but since intensity 1 values are missing, it is difficult to make a definite statement here, except for saying that higher numbers of animals do not result in higher mercury concentrations. The mineral cores of the seasonally frozen soils in Finland show little variation between the different intensities. But, since intensity 3 has strikingly high outliers, it is appropriate to look at the median rather than the mean. The medians of Finland's mineral cores actually increase with intensity. However, the differences between the values are too small to confidently speak of a trend. The fact that intensity 5 shows some higher values here could also be attributed to the fact that the uppermost samples are holding rather recent vegetation. Overall, Figure 9 shows that the Finnish mineral soil sites have slightly lower mercury values than the Chersky cores,

which also consist of mineral soil. Since permanently frozen soils store mercury, while it is more easily washed out and transported in mineral unfrozen soils, this result is reasonable.
For the Chersky samples, the values of intensity 1 sites lie very close together, while they are more scattered for the other intensities. The values here are much smaller than for intensity 3 and 5. Thus, for the permafrost in Chersky, there is a clear difference in mercury concentrations between grazed and ungrazed areas. In contrast, a difference between grazing intensity 3 and 5 appears less pronounced. The fact that intensity 3 nevertheless shows higher values than 5 could possibly be due to the fact that the presence or absence of animals does make a difference, but the difference between the herbivore number and density of intensities 3 and 5 is too minor to show a further increase. In addition, a possible explanation could also be that the animal density at the intensity 3 site does not show stable conditions comparable to intensity 1 or 5, because it has either too much or too little animal activity for one or the other extreme. Furthermore, site B3 is placed on a location that is flooded occasionally and thus experiences potential mercury inputs that the Yedoma sites do not. If such a site existed, a lower mean intensity 3 value would at least be a possibility.
Obviously, the samples of the seasonally frozen soil behave differently than those of the permafrost soil. This is shown by the correlation values of an individual consideration of the two study areas. The corresponding correlation matrices are attached in Appendix C.

As suspected at the beginning of the chapter, the sample set from Finland seems to be trendsetting for the correlation calculations of the overall data set due to its higher sample number. This can be supported by the fact that a singular examination of the Inari data shows mostly the same mercury related trends and similarly high correlation values as those of the merged data set. This remains the case when only the mineral soil samples are considered. Likewise, considering only the peat samples, there is no significant correlation for seasonality with mercury content. The same is true when looking at MGS and mercury. Again, no significant correlation can be found. However, this is due to the fact that no grain sizes are available for the peat samples. All other mercury-related correlations are again consistent with those of the overall data set.

For Chersky, the correlations of depth, MGS, and AWC with mercury yield the same trends with similar correlation values as the equivalents of the merged data set. However, for the consideration of the correlations of the variables soil type and intensity with mercury, opposite trends emerge, while for TOC a non-significant correlation value was calculated. The soil type here correlates negatively with the concentration of mercury, meaning that mineral soils have the higher mercury content than peat soils. This is evident because only one site (B1) with a thin peat layer was present in Chersky, accounting for a total of 5 sampling points. This phenomenon has already been discussed in chapter 4.1. The fact that no correlation could be found for the variables mercury and TOC content seems surprising at

first, since it has already been stated that organic material binds mercury. However, looking at the TOC values for Chersky (see table in Appendix B), it is noticeable that the values of organic carbon, especially in comparison to Inari, are extremely low on the one hand and also show significantly lower fluctuations, which should explain the result of the calculation.
The most relevant difference between the Chersky and the total data / Inari data set is the existing positive correlation between intensity and mercury with a correlation value of 0.34. This result would translate into the statement that with higher herbivore activity, mercury levels increase. This trend, present in Chersky, could reinforce the suggestion that the cooling effect of herbivores on the soil ensures that less mercury is removed and, consequently, greater amounts accumulate in the soil.

For the permafrost soil, it is also useful to investigate possible different behaviors between the active layer and the permafrost layer with regard to potential correlations of the addressed variables with the mercury content. In this context, it should be noted that the split into active and permafrost layers leads to an extremely small number of samples for both categories.
When compared with the Chersky total data set, the active layer shows little difference. However, the mercury-related correlation values for the variables depth (-0.56), intensity (0.52) and AWC (0.84) show the same trend, but are strikingly stronger correlated. This can be explained by the fact that the active layer represents more contemporary events and, in contrast to permafrost, input, transport and output can take place during the unfrozen state in summer. A deviating mercury-related trend is particularly outstanding. This relates to the correlation with the TOC content, which is not significant in the Chersky total data set. For the active layer, on the other hand, a positive correlation of 0.89 can be found. Due to the surface influence on the upper soil layers, the TOC content in the sample closest to the surface as well as in the active layer in general is often higher than in the permafrost, which may explain the divergence from the Chersky total data set. Accordingly, a statement that TOC content in Chersky is probably not an important variable related to mercury concentration must be restricted to the soil layers below the permafrost table.

The permafrost layer behaves differently from the active layer in the sense that no significant correlation could be found for the variables depth, intensity and TOC. As the depth development results already showed, the mercury concentrations of the individual sites are relatively constant and show hardly any fluctuations due to the stable conditions of the permafrost. Because of the similar values of the mercury content, the result of the correlation calculations is reasonable. This implies that the herbivores have an influence mainly on the mercury contents in the active layer of the permafrost soil. Nevertheless, the permanently frozen layers are also protected by the associated soil cooling.

*Table 11: **Ranking of mercury-related correlation values for the merged, Siberian und Finnish data sets.** The table shows the ranked mercury correlations, with the highest correlation value at rank 1 and the lowest correlation value at rank 7 or 6. The rankings of the correlations between mercury and intensity are marked in green.*

Rank	MERGED DATA SET		PERMAFROST - CHERSKY		SFG - FINLAND	
	Correlation Pair	Cor-Value	Correlation Pair	Cor-Value	Correlation Pair	Cor-Value
1	THg - MGS	- 0.58	THg - MGS	- 0.62	THg - TOC	+ 0.44
2	THg - AWC	+ 0.44	THg - AWC	+ 0.51	THg - AWC	+ 0.42
3	THg - TOC	+ 0.41	THg - Depth	- 0.47	THg - Depth	- 0.38
4	THg - Depth	- 0.37	THg - Intensity	+ 0.34	THg - MGS	- 0.33
5	THg - Soiltype	+ 0.25	THg - Soiltype	- 0.30	THg - Soiltype	+ 0.28
6	THg - Seasonality	+ 0.18	THg - TOC	NA	THg - Seasonality	NA
7	THg - Intensity	NA			THg - Intensity	NA

*Table 12: **Ranking of mercury-related correlation values for the Finnish data set, separating mineral and peat cores.** The table shows the ranked mercury correlations, with the highest correlation value at rank 1 and the lowest correlation value at rank 7 or 6. The rankings of the correlations between mercury and intensity are marked in green.*

Rank	SFG – FINLAND TOTAL		SFG – FINLAND - MINERAL		SFG – FINLAND - PEAT	
	Correlation Pair	Cor-Value	Correlation Pair	Cor-Value	Correlation Pair	Cor-Value
1	THg - TOC	+ 0.44	THg - TOC	+ 0.90	THg - Depth	- 0.54
2	THg - AWC	+ 0.42	THg - AWC	+ 0.84	THg - AWC	+ 0.38
3	THg - Depth	- 0.38	THg - Depth	- 0.43	THg - TOC	+ 0.36
4	THg - MGS	- 0.33	THg - MGS	NA	THg - MGS	NA
5	THg - Soiltype	+ 0.28	THg - Seasonality	NA	THg - Seasonality	NA
6	THg - Seasonality	NA	THg - Intensity	NA	THg - Intensity	NA
7	THg - Intensity	NA				

Tables 11 and 12 are ranking the different variables influencing the mercury content in the soil, considering the soil types separately. The greatest influence according to the Pearson correlations is shown by the variables MGS for the permafrost soil in Chersky, TOC for the mineral samples, and depth for the peat samples of the seasonally frozen soil in Finland. As explained earlier, depth is important due to surface influence. Just like absolute water content, TOC content is among the three variables most highly correlated with mercury for both the mineral and peat samples of Finland. For the permafrost soil, on the other hand, it is of no relevance. But, as just shown, this is only true for the joint consideration of the active and permanently frozen layer. Under separate consideration of the active layer, the TOC content is the highest correlating value. As already mentioned, intensity shows no significant correlation for both Finnish soil types, while a direct comparison with the other influencing variables results in a rather low rank for Chersky. Nevertheless, it is not unremarkable with a correlation value of 0.34.

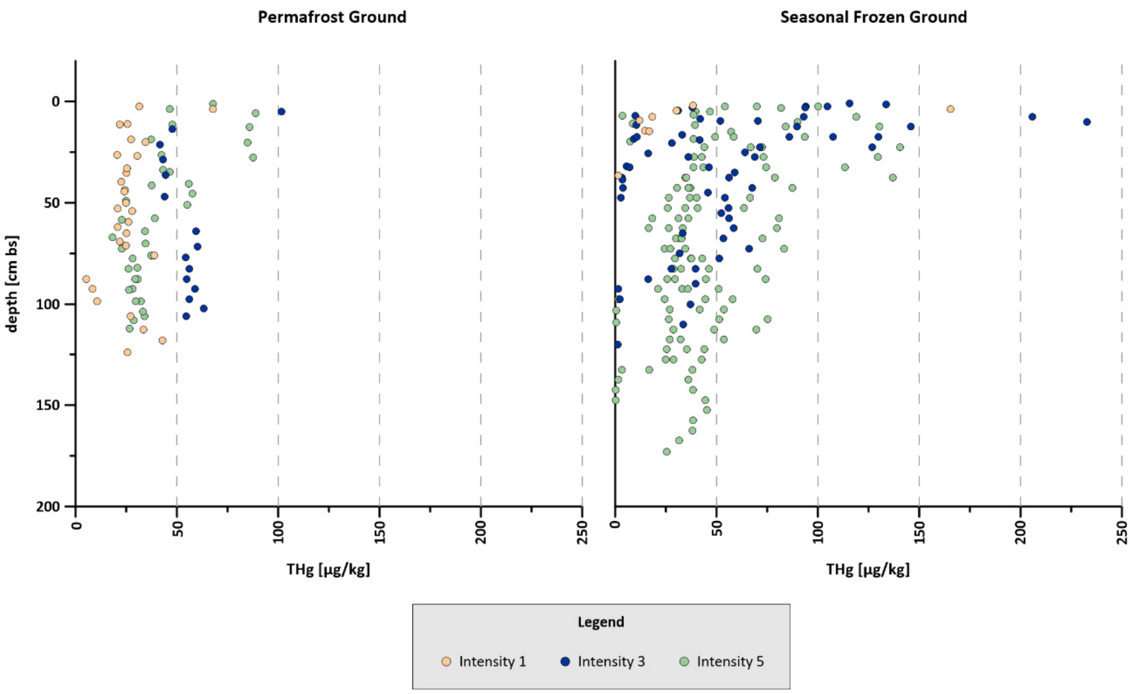

Figure 10: Scatter plot for mercury concentrations of permafrost and seasonal frozen ground. *The figure above plots mercury levels versus depth. The distinction of the different intensities does reveal cluster for permafrost, but not for seasonal frozen ground.*

Finally, the result of the presented analysis can be illustrated by Figure 10. Under direct comparison of the intensities, neither a trend nor the clusters necessary for it in the plot versus depth are shown for the seasonally frozen ground of Finland. A different result can be recognized for the permafrost soil of Chersky

The fact that herbivore activity has an influence on mercury levels in permafrost soils, while this does not seem to be the case for seasonally frozen soils, may thereby possibly be due to the more stable conditions of permafrost, while Inaris soils experience too much fluctuation due to seasonal thawing. Although the Active Layer in Chersky also undergoes seasonal thawing and is also affected by input, output, and transport, the active layer of permafrost soil is not comparable to the upper layer of seasonally frozen soil in this context. The time period of the thawed state of the active layer varies with grazing. With a high number of animals, the duration of the unfrozen state decreases. In addition, with the permanently frozen layer underneath, which further cools the active layer from below, substances cannot escape downward, which contributes to the stabilizing conditions of this soil type.

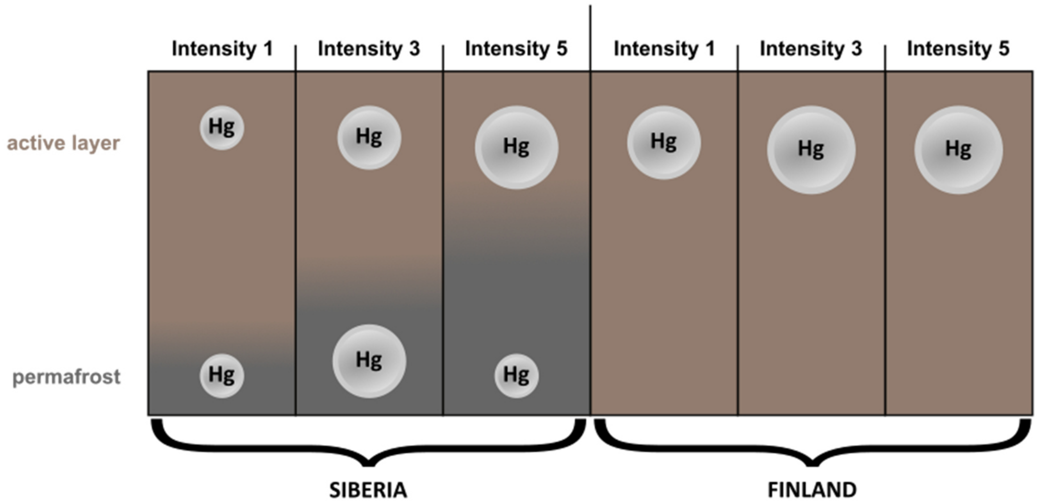

Figure 11: Study results*. Herbivore activity shows no significant effect on mercury levels in seasonally frozen soils. An effect could be detected for permafrost soils.*

4.3 Limitations of the Study Approach

It should be pointed out that the different sample sizes of the various intensities and soil types did have an influence on the results. This could be resolved by a larger sample size in general and, more importantly, a more even distribution of the number of soil cores for the different categories. In addition, it might be worthwhile to consider a long-term study, meaning a long-term monitoring and sampling of ungrazed areas with gradual introduction of herbivores. This would be additionally beneficial in permafrost areas to observe possible thawing and thus possible shifting of the permafrost table.

5 CONCLUSION

Considering the increase of anthropogenically released harmful heavy metals into the environment, as well as the high relevance of Arctic soils, especially permafrost soils, in their role as reservoirs, the objective of this research was to investigate a potential effect of herbivore activity on mercury concentrations in Arctic soils. Based on the soil-cooling influence of the animals through vegetation change in summer and the compression of the snow cover in winter, it was assumed that a difference in mercury content would occur between sites of varying grazing intensities on the study areas investigated for this purpose. The specific assumption that with increasing herbivore activity an increase in the soil mercury content would be observable, since the ground-cooling could provide longer fixation spans of the pollutant, has not been verified for a merged data set of permafrost and seasonally frozen ground. Grazing intensity did not show a significant correlation with soil mercury content. A considered increase in mercury content with depth was also not confirmed for the overall dataset. Instead, a decrease with depth was detectable for most cores, which was attributed to decreasing surface influence and the associated input of mercury through the atmosphere, vegetation, animal dung and flooding. Further, it was suggested that the upper soil layers, due to their ability to reflect more contemporary events, might behave differently or demonstrate the potential effect of animals on mercury levels more clearly. However, the upper 20 cm of soil examined for this purpose did not show any difference from the results that considered the entire core depth. Slightly increased mercury-related correlation values of the considered influencing variables (depth, TOC, AWC and MGS), on the other hand, have been observed.

Furthermore, a separate consideration of the permafrost ground in Siberia and the seasonally frozen ground in Finland was carried out, where, with regard to the research question, clear differences of the two soil types were found. While the Finnish seasonally frozen soils, which were additionally divided into mineral and peat soils for a more differentiated consideration, were mostly in agreement with the results of the merged data set, meaning that no correlation between mercury content and grazing intensity could be detected, the soil cores of Chersky's permafrost behaved differently. In the differentiation of the Finnish mineral and peat soil samples, it was noticeable that the latter showed substantially higher fluctuations as well as generally higher values in regard to the mercury concentration. Taking into account the results of the correlation tests, this was explained by the high TOC content in the peat soil. Due to the adsorbing property of organic matter, this variable showed the most relevant and highest influence on the mercury content for all data sets.

For permafrost sites at Chersky, a clear difference in mercury concentration existed between grazed (intensity 3 and 5) and ungrazed areas (intensity 1). In contrast, a difference between grazing intensities 3 and 5, with 3 having the higher mercury concentrations, was less pronounced. A cause of this phenomenon may be found in insufficiently diverse animal density, insufficient sample size, prevailing vegetation, as well as the occasional flooding of the location. The samples from Chersky showed a positive correlation between grazing intensity and mercury indicating that with higher herbivore activity mercury levels increase. Therefore, the assumption of a cooling effect of herbivores on the soil supporting mercury fixation and accumulation, is reasonable. A further separate consideration of the active layer of the permafrost ground showed, due to the ongoing processes of transport, input and output during the unfrozen phase, stronger results for the correlation tests, with identical mercury-related trends of the influencing variables. On separate consideration, the mercury content of the soil layer below the permafrost table showed no correlation with grazing intensity due to almost uniform values. This indicates that the herbivores mainly influence the mercury levels in the active layer of the permafrost region. Nevertheless, the permanently frozen layers are protected by the associated soil cooling. This statement was supported by the location of the permafrost tables, where intensity 5 shows the shallowest active layer, indicating that thawing was reduced in comparison to sites of lower herbivore activity.

In summary, mercury levels in seasonally frozen ground and permafrost ground behave differently under herbivore influence. While the animals show no effect on the concentration of mercury in seasonally frozen ground, the hypothesis of large herbivores influencing the concentration of soil mercury can be confirmed for permafrost.

In order to exclude the possibility of random results as well as to be able to further observe a possible development of the studied effect, a repetition of the investigation at a later time is advised. In addition, the examination of the different sources of mercury input regarding their extent is necessary to be able to understand mercury related processes in Arctic regions more explicitly.

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APPENDIX

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APPENDIX A: SITE INFORMATION AND CORE DESCRIPTIONS

CHERSKY, SIBERIA

Site	Latitude (°N)	Longitude (°E)	Grazing Intensity	Main Vegetation Type	Flooding Regime	Active Layer Depth [cm bs]	Total Core Length [cm]	Main Sedimental Material
B1	68.512167	161.496278	none	graminoids, forbs and shrubs	occasional	80	127	silt, peat layer (85-115 cm bs)
B3	68.511111	161.508528	occasional	graminoids and forbs	occasional	51	108	clayish silt
B5	68.512694	161.508750	intensive	graminoids	seasonal	38	110	clayish silt
U1	68.504469	161.488390	none	NA	none	NA	72	silt
U5	68.512778	161.514611	intensive	graminoid-rich tundra and shrubs	none	53	114	clayish silt

(Windirsch et al. 2022)

The depth of the active layer is based on the time of sampling; July 2019.

INARI, FINLAND

Site	Latitude (°N)	Longitude (°E)	Grazing Intensity (during season)	Main Vegetation Type	Sampling Depth [cm]	Relief	Soil Type
E-1M-A	69.159500	26.991278	no grazing (~ 50 yrs)	mixed forest, mosses	40.0	flat, dry	mineral (categorized as mineral core)
E-1M-B	69.154113	26.971089	no grazing (~ 50 yrs)	open mixed forest, mosses	17.5	slight slope, dry	mineral (categorized as mineral core)
S-2M	69.159861	26.991250	seldom	mixed forest, mosses	67.0	flat, dry	mineral (categorized as mineral core)
S-2P	69.152357	26.971650	seldom	mixed forest / bog edge	50.0	slope, wet	peat, bedrock below (categorized as peat core)
S-3M	69.139250	26.984000	regularly	heath / grassland	42.0	valley edge, dry	mineral (categorized as mineral core)

S-3P	69.139944	26.983778	regularly	heath / grassland	100.0	valley, wet	peat (0-92 cm), mineral (92-100 cm) (categorized as peat core)
S-4P	69.143500	26.990000	frequently	heath / grassland	143.0	valley, wet	peat (categorized as peat core)
S-5F	69.145806	26.994306	very often	birch forest, grassy understorey	112.0	valley, wet	peat (0-92 cm), mineral (92-112 cm) (categorized as peat core)
S-5P	69.146722	26.993306	very often	grassland	150.0	valley, semi-dry	peat (0-135 cm), mineral (135-150 cm) (categorized as peat core)
S-5M	69.147222	26.991528	very often	grassland	22.0	valley edge, dry	mineral (categorized as mineral core)
W-3M	69.107441	27.015753	regularly	birch forest, shrubby understorey	22.0	slope plateau	mineral (categorized as mineral core)
W-3P	69.103456	27.019161	regularly	heath / grassland	25.0	valley, wet (meltwater run)	peat, bedrock below (categorized as peat core)
W-4M-A	69.109031	27.013619	frequently	birch forest	11.0	bog edge, dry	mineral (categorized as mineral core)
W-4M-B	69.109079	27.013550	frequently	birch forest	26.5	bog edge, dry	mineral (categorized as mineral core)
W-4P	69.119953	27.030306	frequently	bog in a mixed forest clearing	88.0	slight slope	peat (0-66 cm), mineral content (66-88 cm) (categorized as peat core)
W-5M	69.120851	27.026792	very often	forest edge	22.5	dry, flat	mineral (categorized as mineral core)

W-5P-A	69.109076	27.012831	very often	fenn / grassland	135.0	valley, wet	peat (0-133 cm), mineral (133-135 cm) (categorized as peat core)
W-5P-B	69.120867	27.026270	very often	fenn / grassland	176.0	valley, wet	peat (categorized as peat core)
MR	69.229750	26.795806	regularly	mixed forest, shrubby understorey	35.0	flat, dry	mineral (categorized as mineral core)
PR	69.226778	26.810111	regularly	heath / grassland, mosses	125.0	lakeside peatland, wet	peat (0-115 cm), mineral (115-125 cm) (categorized as peat core)
FR	69.226000	26.833417	regularly	birch forest, grassy understorey	50.0	valley, semi-dry	peat (0-30 cm), mineral (30-50 cm) (categorized as peat core)

(Windirsch et al. 2023)

APPENDIX B: Complete data table of the sample series from Siberia 2019 and Finland 2020/22

Sample-ID	Mean Depth [cm bs]	Intensity	Soiltype	THg [µg/kg]	TOC [wt%]	MGS [µm]	AWC [wt%]	State	Seasonality
FI20-MR-1	1.50	3	mineral	133.60	45.38	NA	69.11	unfrozen	year-round
FI20-MR-2	4.50	3	mineral	31.01	7.32	122.30	28.38	unfrozen	year-round
FI20-MR-3	7.00	3	mineral	9.93	1.62	101.10	16.49	unfrozen	year-round
FI20-MR-4	11.50	3	mineral	10.50	0.79	100.90	14.35	unfrozen	year-round
FI20-MR-5	18.50	3	mineral	9.24	0.24	124.80	NA	unfrozen	year-round
FI20-MR-6	25.50	3	mineral	16.26	0.33	105.60	12.98	unfrozen	year-round
FI20-MR-7	32.00	3	mineral	5.65	0.19	118.10	11.41	unfrozen	year-round
FI20-PR-0	1.00	3	peat	115.67	47.80	NA	85.56	unfrozen	year-round
FI20-PR-1	8.50	3	peat	41.94	43.80	NA	79.42	unfrozen	year-round
FI20-PR-2	17.50	3	peat	107.42	46.65	NA	81.48	unfrozen	year-round
FI20-PR-3	25.00	3	peat	64.01	43.00	NA	74.82	unfrozen	year-round
FI20-PR-4	35.00	3	peat	58.96	38.63	NA	69.54	unfrozen	year-round
FI20-PR-5	45.00	3	peat	45.66	37.99	NA	70.14	unfrozen	year-round
FI20-PR-6	55.00	3	peat	52.31	38.97	NA	68.86	unfrozen	year-round
FI20-PR-7	65.00	3	peat	33.41	40.40	NA	76.72	unfrozen	year-round
FI20-PR-8	75.00	3	peat	31.68	42.05	NA	78.26	unfrozen	year-round
FI20-PR-9	82.50	3	peat	39.51	38.23	NA	80.15	unfrozen	year-round
FI20-PR-10	90.00	3	peat	39.69	37.89	NA	82.88	unfrozen	year-round
FI20-PR-11	100.00	3	peat	37.06	23.88	NA	73.61	unfrozen	year-round
FI20-PR-12	110.00	3	peat	33.59	32.65	NA	74.67	unfrozen	year-round
FI20-PR-13	120.00	3	mineral	1.29	1.31	144.20	22.53	unfrozen	year-round

FI20-FR-1	2.50	3	peat	93.96	48.31	NA	85.67	unfrozen	year-round
FI20-FR-2	7.50	3	peat	205.74	49.00	NA	55.41	unfrozen	year-round
FI20-FR-3	12.50	3	peat	145.74	37.67	NA	82.17	unfrozen	year-round
FI20-FR-4	17.50	3	peat	129.78	36.26	NA	81.53	unfrozen	year-round
FI20-FR-5	22.50	3	peat	126.80	31.93	NA	75.30	unfrozen	year-round
FI20-FR-6	27.50	3	peat	35.98	10.03	58.35	57.36	unfrozen	year-round
FI20-FR-7	32.50	3	mineral	7.24	2.37	196.70	22.15	unfrozen	year-round
FI20-FR-8	37.50	3	mineral	3.35	0.98	107.20	16.88	unfrozen	year-round
FI20-FR-9	42.50	3	mineral	3.78	0.78	101.90	15.59	unfrozen	year-round
FI20-FR-10	47.50	3	mineral	2.84	1.08	123.40	19.18	unfrozen	year-round
FI20-E-1M-A-1	2.00	1	mineral	38.46	11.98	NA	40.83	unfrozen	year-round
FI20-E-1M-A-2	4.50	1	mineral	30.33	2.70	226.80	17.30	unfrozen	year-round
FI20-E-1M-A-3	7.50	1	mineral	18.27	1.78	131.20	17.03	unfrozen	year-round
FI20-E-1M-A-4	14.50	1	mineral	14.84	1.47	180.20	12.72	unfrozen	year-round
FI20-E-1M-A-5	36.50	1	mineral	1.48	0.32	222.10	7.53	unfrozen	year-round
FI20-S-2M-1	1.00	2	mineral	95.12	22.97	NA	59.69	unfrozen	summer
FI20-S-2M-2	3.00	2	mineral	3.93	1.3	165.00	14.33	unfrozen	summer
FI20-S-2M-3	10.50	2	mineral	20.78	1.86	199.90	15.58	unfrozen	summer
FI20-S-2M-4	18.50	2	mineral	2.55	0.43	318.90	6.54	unfrozen	summer
FI20-S-2M-5	33.50	2	mineral	4.05	0.45	177.80	11.07	unfrozen	summer
FI20-S-2M-6	43.50	2	mineral	1.06	0.11	253.00	6.48	unfrozen	summer
FI20-S-2M-7	58.00	2	mineral	0.84	0.1	322.30	3.37	unfrozen	summer
FI20-S-2M-8	63.50	2	mineral	1.00	0.13	232.60	5.89	unfrozen	summer
FI20-S-3M-1	3.00	3	mineral	93.66	49.01	NA	77.10	unfrozen	summer

FI20-S-3M-2	9.50	3	mineral	51.88	16.07	67.88	56.08	unfrozen	summer
FI20-S-3M-3	16.50	3	mineral	33.15	14.42	76.30	37.04	unfrozen	summer
FI20-S-3M-4	38.50	3	mineral	3.54	1.06	69.31	16.31	unfrozen	summer
FI20-S-3P-1	3.00	3	peat	38.20	46.11	NA	90.27	unfrozen	summer
FI20-S-3P-2	9.50	3	peat	70.29	46.56	NA	89.16	unfrozen	summer
FI20-S-3P-3	19.00	3	peat	41.60	27.56	NA	88.55	unfrozen	summer
FI20-S-3P-4	27.50	3	peat	68.97	47.59	NA	89.36	unfrozen	summer
FI20-S-3P-5	32.50	3	peat	46.30	46.22	NA	88.01	unfrozen	summer
FI20-S-3P-6	37.50	3	peat	56.12	47.47	NA	88.04	unfrozen	summer
FI20-S-3P-7	42.50	3	peat	67.60	47.28	NA	83.36	unfrozen	summer
FI20-S-3P-8	47.50	3	peat	54.22	52.91	NA	85.33	unfrozen	summer
FI20-S-3P-9	52.50	3	peat	56.03	51.30	NA	87.03	unfrozen	summer
FI20-S-3P-10	57.50	3	peat	56.09	51.54	NA	84.07	unfrozen	summer
FI20-S-3P-11	62.50	3	peat	58.48	51.26	NA	80.70	unfrozen	summer
FI20-S-3P-12	67.50	3	peat	53.27	55.08	NA	75.98	unfrozen	summer
FI20-S-3P-A-13	72.50	3	peat	66.16	52.89	NA	75.51	unfrozen	summer
FI20-S-3P-A-14	77.50	3	peat	51.25	26.21	NA	67.48	unfrozen	summer
FI20-S-3P-A-15	82.50	3	peat	27.81	13.47	NA	55.49	unfrozen	summer
FI20-S-3P-A-16	87.50	3	peat	16.16	8.14	93.57	51.96	unfrozen	summer
FI20-S-3P-A-17	92.50	3	peat	1.64	1.58	NA	25.72	unfrozen	summer
FI20-S-3P-A-18	97.50	3	mineral	2.26	0.56	98.2	16.47	unfrozen	summer
FI20-S-4P-A-1	2.50	4	peat	188.39	48.84	NA	83.5	unfrozen	summer
FI20-S-4P-A-2	7.50	4	peat	218.22	49.91	NA	83.79	unfrozen	summer
FI20-S-4P-A-3	12.50	4	peat	104.01	48.31	NA	87.68	unfrozen	summer

FI20-S-4P-A-4	17.50	4	peat	72.60	47.36	NA	89.61	unfrozen	summer
FI20-S-4P-A-5	22.50	4	peat	41.56	46.85	NA	90.83	unfrozen	summer
FI20-S-4P-A-6	27.50	4	peat	34.05	48.35	NA	88.31	unfrozen	summer
FI20-S-4P-A-7	32.50	4	peat	38.62	47.25	NA	NA	unfrozen	summer
FI20-S-4P-A-8	37.50	4	peat	79.88	51.44	NA	80.31	unfrozen	summer
FI20-S-4P-A-9	42.50	4	peat	78.89	50.58	NA	79.52	unfrozen	summer
FI20-S-4P-A-10	47.50	4	peat	61.99	52.27	NA	77.91	unfrozen	summer
FI20-S-4P-A-11	52.50	4	peat	51.20	54.64	NA	80.44	unfrozen	summer
FI20-S-4P-A-12	57.50	4	peat	80.26	55.67	NA	80.98	unfrozen	summer
FI20-S-4P-A-13	62.50	4	peat	60.09	54.87	NA	83.69	unfrozen	summer
FI20-S-4P-A-14	67.50	4	peat	29.72	51.92	NA	83.65	unfrozen	summer
FI20-S-4P-A-15	72.50	4	peat	17.59	54.02	NA	86.83	unfrozen	summer
FI20-S-4P-A-16	77.50	4	peat	19.43	50.78	NA	84.45	unfrozen	summer
FI20-S-4P-A-17	82.50	4	peat	20.46	53.99	NA	86.64	unfrozen	summer
FI20-S-4P-A-18	87.50	4	peat	14.68	52.57	NA	87.54	unfrozen	summer
FI20-S-4P-A-19	92.50	4	peat	14.80	50.93	NA	88.14	unfrozen	summer
FI20-S-4P-A-20	97.50	4	peat	20.50	53.27	NA	87.25	unfrozen	summer
FI20-S-4P-21	102.50	4	peat	32.19	51.86	NA	86.68	unfrozen	summer
FI20-S-4P-22	107.50	4	peat	39.30	52.87	NA	86.93	unfrozen	summer
FI20-S-4P-23	112.50	4	peat	45.65	50.59	NA	86.16	unfrozen	summer
FI20-S-4P-24	117.50	4	peat	36.25	45.67	NA	83.54	unfrozen	summer
FI20-S-4P-25	122.50	4	peat	19.59	44.31	NA	85.36	unfrozen	summer
FI20-S-4P-26	127.50	4	peat	44.28	49.61	NA	85.38	unfrozen	summer
FI20-S-4P-27	132.50	4	peat	54.26	43.91	NA	85.8	unfrozen	summer

FI20-S-4P-28	137.50	4	peat	54.70	40.51	NA	85.25	unfrozen	summer
FI20-S-4P-29	141.50	4	peat	58.36	45.35	NA	85.51	unfrozen	summer
FI20-S-5F-1	2.50	5	peat	100.19	47.94	NA	87.13	unfrozen	summer
FI20-S-5F-2	7.50	5	peat	118.80	50.86	NA	85.37	unfrozen	summer
FI20-S-5F-3	12.50	5	peat	130.26	49.73	NA	85.71	unfrozen	summer
FI20-S-5F-4	17.50	5	peat	93.46	50.11	NA	85.84	unfrozen	summer
FI20-S-5F-5	22.50	5	peat	72.37	49.32	NA	85.86	unfrozen	summer
FI20-S-5F-6	27.50	5	peat	73.07	50.57	NA	82.81	unfrozen	summer
FI20-S-5F-7	32.50	5	peat	74.50	54.90	NA	81.51	unfrozen	summer
FI20-S-5F-8	37.50	5	peat	78.80	54.57	NA	82.57	unfrozen	summer
FI20-S-5F-9	42.50	5	peat	37.06	53.04	NA	85.39	unfrozen	summer
FI20-S-5F-10	47.50	5	peat	26.42	50.60	NA	87.29	unfrozen	summer
FI20-S-5F-11	52.50	5	peat	25.80	52.77	NA	87.54	unfrozen	summer
FI20-S-5F-12	57.50	5	peat	18.27	50.61	NA	88.48	unfrozen	summer
FI20-S-5F-13	62.50	5	peat	26.48	53.19	NA	86.30	unfrozen	summer
FI20-S-5F-14	67.50	5	peat	31.90	53.40	NA	86.46	unfrozen	summer
FI20-S-5F-15	72.50	5	peat	24.36	54.04	NA	85.50	unfrozen	summer
FI20-S-5F-16	77.50	5	peat	37.40	52.41	NA	85.57	unfrozen	summer
FI20-S-5F-17	82.50	5	peat	46.17	50.36	NA	85.16	unfrozen	summer
FI20-S-5F-18	87.50	5	peat	44.62	40.74	NA	82.09	unfrozen	summer
FI20-S-5F-19	92.50	5	peat	32.98	24.39	NA	73.96	unfrozen	summer
FI20-S-5F-20	97.50	5	mineral	1.58	3.12	150.40	39.87	unfrozen	summer
FI20-S-5F-21	103.00	5	mineral	0.37	1.40	293.80	29.62	unfrozen	summer
FI20-S-5F-22	109.00	5	mineral	0.43	0.54	335.10	16.78	unfrozen	summer

FI20-S-5P-1	2.50	5	peat	69.79	45.34	NA	81.04	unfrozen	summer
FI20-S-5P-2	10.00	5	peat	89.90	48.98	NA	86.48	unfrozen	summer
FI20-S-5P-3	17.50	5	peat	49.17	53.16	NA	80.85	unfrozen	summer
FI20-S-5P-4	22.50	5	peat	66.72	53.58	NA	79.88	unfrozen	summer
FI20-S-5P-5	27.50	5	peat	42.79	53.91	NA	78.91	unfrozen	summer
FI20-S-5P-6	32.50	5	peat	43.37	52.63	NA	81.08	unfrozen	summer
FI20-S-5P-7	37.50	5	peat	34.50	53.33	NA	82.85	unfrozen	summer
FI20-S-5P-8	42.50	5	peat	36.03	53.99	NA	84.12	unfrozen	summer
FI20-S-5P-9	47.50	5	peat	40.16	54.02	NA	84.33	unfrozen	summer
FI20-S-5P-10	52.50	5	peat	40.77	53.87	NA	84.19	unfrozen	summer
FI20-S-5P-11	57.50	5	peat	36.05	52.26	NA	84.26	unfrozen	summer
FI20-S-5P-12	62.50	5	peat	16.48	51.02	NA	85.05	unfrozen	summer
FI20-S-5P-13	67.50	5	peat	30.04	43.74	NA	77.69	unfrozen	summer
FI20-S-5P-14	72.50	5	peat	34.61	52.17	NA	86.35	unfrozen	summer
FI20-S-5P-15	77.50	5	peat	37.56	52.59	NA	86.41	unfrozen	summer
FI20-S-5P-16	82.50	5	peat	32.44	50.93	NA	86.14	unfrozen	summer
FI20-S-5P-17	87.50	5	peat	29.47	49.64	NA	86.94	unfrozen	summer
FI20-S-5P-18	92.50	5	peat	35.79	50.91	NA	87.6	unfrozen	summer
FI20-S-5P-19	97.50	5	peat	57.86	49.12	NA	87.31	unfrozen	summer
FI20-S-5P-20	102.50	5	peat	41.56	46.21	NA	87.12	unfrozen	summer
FI20-S-5P-21	107.50	5	peat	51.24	44.71	NA	87.09	unfrozen	summer
FI20-S-5P-22	112.50	5	peat	48.73	45.18	NA	87.15	unfrozen	summer
FI20-S-5P-23	117.50	5	peat	32.34	43.65	NA	86.49	unfrozen	summer
FI20-S-5P-24	122.50	5	peat	35.28	42.00	NA	86.01	unfrozen	summer

FI20-S-5P-25	127.50	5	peat	24.78	23.79	NA	77.02	unfrozen	summer
FI20-S-5P-26	132.50	5	peat	3.40	3.25	31.82	36.44	unfrozen	summer
FI20-S-5P-27	137.50	5	mineral	1.55	0.74	103.50	23.13	unfrozen	summer
FI20-S-5P-28	142.50	5	mineral	0.24	0.24	84.89	15.02	unfrozen	summer
FI20-S-5P-29	147.50	5	mineral	0.22	0.58	103.20	12.72	unfrozen	summer
FI20-S-5M-1	2.50	5	mineral	54.02	22.47	NA	69.77	unfrozen	summer
FI20-S-5M-2	7.00	5	mineral	3.64	1.17	90.73	17.31	unfrozen	summer
FI20-S-5M-3	11.50	5	mineral	39.35	4.00	43.92	26.23	unfrozen	summer
FI20-S-5M-4	18.50	5	mineral	38.51	1.17	38.02	18.96	unfrozen	summer
FI20-S-2M (Dung)	-8.00	2	NA	87.24	NA	NA	NA	unfrozen	summer
FI22-E-1M-B-1	3.75	1	mineral	165.45	30.59	NA	61.30	unfrozen	year-round
FI22-E-1M-B-2	9.25	1	mineral	11.99	1.94	129.90	27.37	unfrozen	year-round
FI22-E-1M-B-3	14.75	1	mineral	16.87	2.48	149.80	28.10	unfrozen	year-round
FI22-W-2P-1	5.00	2	peat	31.10	46.98	NA	88.8	unfrozen	summer
FI22-W-2P-2	15.00	2	peat	47.19	44.3	NA	90.59	unfrozen	summer
FI22-W-2P-3	25.00	2	peat	67.00	45.13	NA	91.92	unfrozen	summer
FI22-W-2P-4	32.50	2	peat	140.68	48.12	NA	88.57	unfrozen	summer
FI22-W-2P-5	37.50	2	peat	122.03	46.93	NA	89.22	unfrozen	summer
FI22-W-2P-6	42.50	2	peat	52.15	27.21	NA	75.27	unfrozen	summer
FI22-W-2P-7	47.50	2	peat	80.05	50.31	NA	86.19	unfrozen	summer
FI22-W-3M-A-1	10.00	3	mineral	232.68	51.23	NA	81.12	unfrozen	winter
FI22-W-3M-A-2	17.50	3	mineral	10.61	1.98	63.86	26.01	unfrozen	winter
FI22-W-3M-A-3	20.50	3	mineral	27.85	4.29	113.00	27.53	unfrozen	winter
FI22-W-3P-A-1	2.50	3	peat	104.79	48.6	NA	84.1	unfrozen	winter

FI22-W-3P-A-2	7.50	3	peat	92.91	48.75	NA	84.37	unfrozen	winter
FI22-W-3P-A-3	12.50	3	peat	89.61	48.40	NA	84.51	unfrozen	winter
FI22-W-3P-A-4	17.50	3	peat	85.99	47.98	NA	85.81	unfrozen	winter
FI22-W-3P-A-5	22.50	3	peat	71.40	50.59	NA	NA	unfrozen	winter
FI22-W-4P-A-1	2.50	4	peat	25.80	43.72	NA	90.60	unfrozen	winter
FI22-W-4P-A-2	7.50	4	peat	70.77	46.33	NA	88.89	unfrozen	winter
FI22-W-4P-A-3	12.50	4	peat	61.04	43.77	NA	92.21	unfrozen	winter
FI22-W-4P-A-4	17.50	4	peat	74.96	43.45	NA	92.82	unfrozen	winter
FI22-W-4P-A-5	22.50	4	peat	95.04	43.34	NA	88.96	unfrozen	winter
FI22-W-4P-A-6	27.50	4	peat	68.53	38.28	NA	85.61	unfrozen	winter
FI22-W-4P-A-7	32.50	4	peat	75.56	45.4	NA	85.64	unfrozen	winter
FI22-W-4P-A-8	37.50	4	peat	75.90	51.09	NA	84.52	unfrozen	winter
FI22-W-4P-A-9	42.50	4	peat	65.11	52.53	NA	82.75	unfrozen	winter
FI22-W-4P-A-10	47.50	4	peat	58.35	51.41	NA	85.28	unfrozen	winter
FI22-W-4P-A-11	52.50	4	peat	52.27	49.54	NA	86.53	unfrozen	winter
FI22-W-4P-A-12	57.50	4	peat	65.68	52.11	NA	83.80	unfrozen	winter
FI22-W-4P-A-13	62.50	4	peat	84.62	51.90	NA	83.94	unfrozen	winter
FI22-W-4P-A-14	67.50	4	peat	125.71	53.20	NA	81.25	unfrozen	winter
FI22-W-4P-A-15	72.50	4	peat	103.28	46.79	NA	78.97	unfrozen	winter
FI22-W-4P-A-16	77.50	4	peat	119.83	33.84	49.21	69.42	unfrozen	winter
FI22-W-4P-A-17	82.00	4	peat	65.99	12.07	49.57	52.74	unfrozen	winter
FI22-W-4P-A-18	86.00	4	peat	79.31	11.25	62.37	53.95	unfrozen	winter
FI22-W-4M-A-1	2.00	4	mineral	110.67	26.03	NA	48.68	unfrozen	winter
FI22-W-4M-A-2	5.25	4	mineral	8.50	1.48	89.68	19.05	unfrozen	winter

FI22-W-4M-A-3	8.75	4	mineral	14.60	1.69	200.90	14.35	unfrozen	winter
FI22-W-4M-B-1	4.75	4	mineral	63.56	11.49	NA	47.41	unfrozen	winter
FI22-W-4M-B-2	11.50	4	mineral	8.96	1.30	260.70	10.71	unfrozen	winter
FI22-W-4M-B-3	23.75	4	mineral	14.57	1.38	113.70	17.99	unfrozen	winter
FI22-W-5P-A-1	5.00	5	peat	39.64	45.82	NA	89.02	unfrozen	winter
FI22-W-5P-A-2	15.00	5	peat	57.20	44.70	NA	90.25	unfrozen	winter
FI22-W-5P-A-3	22.50	5	peat	140.40	46.25	NA	90.56	unfrozen	winter
FI22-W-5P-A-4	27.50	5	peat	129.48	47.54	NA	89.07	unfrozen	winter
FI22-W-5P-A-5	32.50	5	peat	113.30	51.12	NA	84.72	unfrozen	winter
FI22-W-5P-A-6	37.50	5	peat	137.01	53.38	NA	81.14	unfrozen	winter
FI22-W-5P-A-7	42.50	5	peat	87.30	28.17	NA	69.55	unfrozen	winter
FI22-W-5P-A-8	47.50	5	peat	66.70	18.45	NA	65.65	unfrozen	winter
FI22-W-5P-A-9	52.50	5	peat	63.41	17.62	NA	65.48	unfrozen	winter
FI22-W-5P-A-10	57.50	5	peat	80.82	20.41	NA	71.41	unfrozen	winter
FI22-W-5P-A-11	62.50	5	peat	79.67	21.74	NA	72.69	unfrozen	winter
FI22-W-5P-A-12	67.50	5	peat	72.80	16.84	NA	69.14	unfrozen	winter
FI22-W-5P-A-13	72.50	5	peat	83.34	23.16	NA	74.74	unfrozen	winter
FI22-W-5P-A-14	77.50	5	peat	42.85	23.49	NA	70.36	unfrozen	winter
FI22-W-5P-A-15	82.50	5	peat	70.09	31.75	NA	77.79	unfrozen	winter
FI22-W-5P-A-16	87.50	5	peat	74.08	43.86	NA	81.53	unfrozen	winter
FI22-W-5P-A-17	92.50	5	peat	51.11	47.30	NA	82.83	unfrozen	winter
FI22-W-5P-A-18	97.50	5	peat	44.48	39.90	NA	82.58	unfrozen	winter
FI22-W-5P-A-19	102.50	5	peat	53.72	27.40	NA	78.53	unfrozen	winter
FI22-W-5P-A-20	107.50	5	peat	75.30	32.67	NA	80.96	unfrozen	winter

FI22-W-5P-A-21	112.50	5	peat	69.65	40.17	NA	82.39	unfrozen	winter
FI22-W-5P-A-22	117.50	5	peat	53.50	47.51	NA	84.57	unfrozen	winter
FI22-W-5P-A-23	122.50	5	peat	43.90	39.30	NA	82.98	unfrozen	winter
FI22-W-5P-A-24	127.50	5	peat	42.73	29.47	NA	78.49	unfrozen	winter
FI22-W-5P-A-25	132.50	5	mineral	16.66	9.91	29.85	52.74	unfrozen	winter
FI22-W-P5-B-1	5.00	5	peat	46.68	41.02	NA	93.19	unfrozen	winter
FI22-W-P5-B-2	12.50	5	peat	84.04	40.34	NA	89.84	unfrozen	winter
FI22-W-P5-B-3	17.50	5	peat	58.56	39.31	NA	88.96	unfrozen	winter
FI22-W-P5-B-4	22.50	5	peat	43.86	41.21	NA	88.81	unfrozen	winter
FI22-W-P5-B-5	27.50	5	peat	38.75	40.62	NA	88.28	unfrozen	winter
FI22-W-P5-B-6	32.50	5	peat	38.73	44.26	NA	88.52	unfrozen	winter
FI22-W-P5-B-7	37.50	5	peat	35.17	47.50	NA	87.61	unfrozen	winter
FI22-W-P5-B-8	42.50	5	peat	30.52	46.81	NA	86.40	unfrozen	winter
FI22-W-P5-B-9	47.50	5	peat	36.91	50.20	NA	88.35	unfrozen	winter
FI22-W-P5-B-10	52.50	5	peat	34.49	48.61	NA	88.67	unfrozen	winter
FI22-W-P5-B-11	57.50	5	peat	31.23	49.57	NA	88.84	unfrozen	winter
FI22-W-P5-B-12	62.50	5	peat	33.21	49.66	NA	87.79	unfrozen	winter
FI22-W-P5-B-13	67.50	5	peat	32.87	48.67	NA	86.86	unfrozen	winter
FI22-W-P5-B-14	72.50	5	peat	27.16	47.99	NA	86.25	unfrozen	winter
FI22-W-P5-B-15	77.50	5	peat	29.38	46.12	NA	86.00	unfrozen	winter
FI22-W-P5-B-16	82.50	5	peat	28.68	45.42	NA	86.02	unfrozen	winter
FI22-W-P5-B-17	87.50	5	peat	25.75	42.22	NA	84.77	unfrozen	winter
FI22-W-P5-B-18	92.50	5	peat	21.13	39.01	NA	83.51	unfrozen	winter
FI22-W-P5-B-19	97.50	5	peat	24.37	44.37	NA	84.27	unfrozen	winter

FI22-W-P5-B-20	102.50	5	peat	27.06	44.62	NA	84.83	unfrozen	winter
FI22-W-P5-B-21	107.50	5	peat	26.46	42.62	NA	83.82	unfrozen	winter
FI22-W-P5-B-22	112.50	5	peat	28.76	46.79	NA	84.84	unfrozen	winter
FI22-W-P5-B-23	117.50	5	peat	26.88	49.06	NA	85.61	unfrozen	winter
FI22-W-P5-B-24	122.50	5	peat	25.29	45.82	NA	84.83	unfrozen	winter
FI22-W-P5-B-25	127.50	5	peat	28.76	51.65	NA	84.80	unfrozen	winter
FI22-W-P5-B-26	132.50	5	peat	38.09	49.93	NA	84.46	unfrozen	winter
FI22-W-P5-B-27	137.50	5	peat	35.98	50.26	NA	86.34	unfrozen	winter
FI22-W-P5-B-28	142.50	5	peat	38.47	48.87	NA	85.40	unfrozen	winter
FI22-W-P5-B-29	147.50	5	peat	44.48	48.31	NA	83.58	unfrozen	winter
FI22-W-P5-B-30	152.50	5	peat	45.16	51.69	NA	84.97	unfrozen	winter
FI22-W-P5-B-31	157.50	5	peat	38.32	52.83	NA	85.38	unfrozen	winter
FI22-W-P5-B-32	162.50	5	peat	38.11	48.77	NA	85.09	unfrozen	winter
FI22-W-P5-B-33	167.50	5	peat	31.49	48.59	NA	86.31	unfrozen	winter
FI22-W-P5-B-34	173.00	5	peat	25.42	38.75	NA	86.06	unfrozen	winter
FI22-W-5M-A-1	3.25	5	mineral	81.82	20.19	NA	54.00	unfrozen	winter
FI22-W-5M-A-2	6.50	5	mineral	38.69	6.28	86.54	34.27	unfrozen	winter
FI22-W-5M-A-3	10.75	5	mineral	8.67	0.94	97.09	18.02	unfrozen	winter
FI22-W-5M-A-4	19.75	5	mineral	7.33	0.44	116.60	13.33	unfrozen	winter
CH19-B5 0 - 2.5	1.25	5	mineral	67.94	16.96	7.16	78.59	unfrozen	year-round
CH19-B5 2.5 - 9	5.75	5	mineral	88.89	17.61	7.83	76.28	unfrozen	year-round
CH19-B5 9 - 16.5	12.75	5	mineral	85.87	20.71	5.66	75.97	unfrozen	year-round
CH19-B5 16.5 - 24	20.25	5	mineral	84.89	25.66	4.56	76.66	unfrozen	year-round
CH19-B5 24 - 31.5	27.75	5	mineral	87.72	23.69	7.10	70.93	unfrozen	year-round

CH19-B5 31.5 - 38	34.75	5	mineral	46.56	5.10	5.41	27.67	unfrozen	year-round
CH19-B5 38 - 43	40.50	5	mineral	55.96	10.25	5.19	47.30	frozen	year-round
CH19-B5 43 - 48	45.50	5	mineral	57.79	11.76	4.81	53.07	frozen	year-round
CH19-B5 48 - 54	51.00	5	mineral	55.04	9.98	6.00	48.99	frozen	year-round
CH19-B5 54 - 61	57.50	5	mineral	39.10	4.97	6.46	31.48	frozen	year-round
CH19-B5 61 - 67	64.00	5	mineral	34.27	5.64	8.00	30.91	frozen	year-round
CH19-B5 67 - 73	70.00	5	mineral	34.48	4.05	7.29	28.22	frozen	year-round
CH19-B5 73 - 79	76.00	5	mineral	37.26	4.90	7.32	31.02	frozen	year-round
CH19-B5 79 - 85	82.00	5	mineral	30.51	3.98	9.87	37.97	frozen	year-round
CH19-B5 85 - 90	87.50	5	mineral	30.66	1.23	15.72	60.83	frozen	year-round
CH19-B5 90 - 95	92.50	5	mineral	28.25	1.18	16.05	62.16	frozen	year-round
CH19-B5 95 - 102	98.50	5	mineral	32.35	1.22	16.08	55.13	frozen	year-round
CH19-B5 102 - 110	106.00	5	mineral	34.02	2.01	16.05	51.05	frozen	year-round
CH19-B3 0 - 10	5.00	3	mineral	101.57	25.02	7.15	64.37	unfrozen	year-round
CH19-B3 10 - 17.5	13.75	3	mineral	47.67	5.93	5.21	49.33	unfrozen	year-round
CH19-B3 17.5 - 25	21.25	3	mineral	41.56	4.89	8.02	32.46	unfrozen	year-round
CH19-B3 25 - 32.5	28.75	3	mineral	43.27	6.08	9.79	34.26	unfrozen	year-round
CH19-B3 32.5 - 40	36.25	3	mineral	44.39	8.15	9.28	43.20	unfrozen	year-round
CH19-B3 43 - 51	47.00	3	mineral	43.96	18.34	7.44	58.40	unfrozen	year-round
CH19-B3 59 - 69	64.00	3	mineral	59.44	30.1	6.90	54.91	unfrozen	year-round
CH19-B3 69 - 74	71.50	3	mineral	60.28	21.13	6.41	65.86	frozen	year-round
CH19-B3 74 - 80	77.00	3	mineral	54.26	14.94	6.12	68.72	frozen	year-round
CH19-B3 80 - 85	82.50	3	mineral	56.04	17.23	5.38	71.10	frozen	year-round
CH19-B3 85 - 90	87.50	3	mineral	54.97	14.71	5.84	67.85	frozen	year-round

CH19-B3 90 - 95	92.50	3	mineral	59.03	13.03	5.84	68.70	frozen	year-round
CH19-B3 95 - 100	97.50	3	mineral	56.06	15.04	5.90	64.18	frozen	year-round
CH19-B3 100 - 104	102.00	3	mineral	63.34	13.76	5.90	68.35	frozen	year-round
CH19-B3 104 - 108	106.00	3	mineral	54.63	9.87	5.89	56.49	frozen	year-round
CH19-B1 0 - 7.5	3.75	1	mineral	67.77	9.65	11.07	39.36	unfrozen	year-round
CH19-B1 7.5 - 15	11.25	1	mineral	21.74	2.28	12.67	21.84	unfrozen	year-round
CH19-B1 15 - 22.5	18.75	1	mineral	27.49	2.01	13.72	20.53	unfrozen	year-round
CH19-B1 22.5 - 30	26.25	1	mineral	20.44	0.81	13.11	17.44	unfrozen	year-round
CH19-B1 31.5 - 39	35.25	1	mineral	25.24	0.79	11.59	17.19	unfrozen	year-round
CH19-B1 40 - 47.5	43.75	1	mineral	24.33	0.87	15.44	17.88	unfrozen	year-round
CH19-B1 47.5 - 58	52.75	1	mineral	20.78	1.04	9.02	18.59	unfrozen	year-round
CH19-B1 58 - 66	62.00	1	mineral	20.88	1.62	13.81	19.32	unfrozen	year-round
CH19-B1 66 - 72	69.00	1	mineral	21.75	2.25	11.47	21.46	unfrozen	year-round
CH19-B1 72 - 80	76.00	1	mineral	38.75	7.75	6.11	34.52	unfrozen	year-round
CH19-B1 85 - 90	87.50	1	peat	5.38	51.40	NA	72.56	frozen	year-round
CH19-B1 90 - 95	92.50	1	peat	8.48	52.80	NA	71.06	frozen	year-round
CH19-B1 95 - 102	98.50	1	peat	10.54	50.31	NA	67.46	frozen	year-round
CH19-B1 102 - 110	106.00	1	peat	27.17	38.13	NA	84.11	frozen	year-round
CH19-B1 110 - 115	112.50	1	peat	33.48	36.56	11.77	85.74	frozen	year-round
CH19-B1 115 - 121	118.00	1	mineral	42.93	8.63	9.53	61.56	frozen	year-round
CH19-B1 121 - 127	124.00	1	mineral	25.69	1.50	9.70	39.59	frozen	year-round
CH19-U5 0 - 7.5	3.75	5	mineral	46.57	4.53	7.26	22.11	unfrozen	year-round
CH19-U5 7.5 - 15	11.25	5	mineral	47.69	3.52	7.18	32.00	unfrozen	year-round
CH19-U5 15 - 22.5	18.75	5	mineral	37.44	3.90	5.58	26.52	unfrozen	year-round

CH19-U5 22.5 - 30	26.25	5	mineral	42.37	4.25	5.50	31.18	unfrozen	year-round
CH19-U5 30 - 37.5	33.75	5	mineral	43.16	4.73	6.05	32.07	unfrozen	year-round
CH19-U5 37.5 - 45	41.25	5	mineral	37.58	5.91	5.34	40.55	unfrozen	year-round
CH19-U5 45 - 53	49.00	5	mineral	24.96	10.14	5.09	55.01	unfrozen	year-round
CH19-U5 53 - 64	58.50	5	mineral	22.86	2.65	9.05	42.84	frozen	year-round
CH19-U5 64 - 70	67.00	5	mineral	18.32	1.68	12.16	30.54	frozen	year-round
CH19-U5 70 - 75	72.50	5	mineral	22.91	1.38	13.91	26.65	frozen	year-round
CH19-U5 75 - 80	77.50	5	mineral	28.12	1.31	12.37	23.44	frozen	year-round
CH19-U5 80 - 85	82.50	5	mineral	26.07	1.05	12.56	19.14	frozen	year-round
CH19-U5 85 - 90	87.50	5	mineral	29.40	1.05	13.54	15.59	frozen	year-round
CH19-U5 90 - 96	93.00	5	mineral	26.33	1.10	13.49	17.93	frozen	year-round
CH19-U5 96 - 101	98.50	5	mineral	29.64	1.03	15.47	22.49	frozen	year-round
CH19-U5 101 - 106	103.50	5	mineral	33.28	1.01	20.15	27.50	frozen	year-round
CH19-U5 106 - 110	108.00	5	mineral	28.64	1.07	14.31	31.52	frozen	year-round
CH19-U5 110 - 114	112.00	5	mineral	26.65	1.19	19.23	31.93	frozen	year-round
CH19-U1 0 - 5	2.50	1	mineral	31.57	1.96	13.14	43.24	frozen	year-round
CH19-U1 7 - 15	11.00	1	mineral	25.55	1.69	12.22	39.70	frozen	year-round
CH19-U1 17 - 23	20.00	1	mineral	34.64	2.41	13.37	43.52	frozen	year-round
CH19-U1 23 - 31	27.00	1	mineral	30.52	2.54	12.26	36.97	frozen	year-round
CH19-U1 31 - 35	33.00	1	mineral	25.34	1.24	11.91	35.41	frozen	year-round
CH19-U1 37 - 42	39.50	1	mineral	22.55	1.37	14.31	25.63	frozen	year-round
CH19-U1 42 - 47	44.50	1	mineral	24.20	1.32	12.27	25.76	frozen	year-round
CH19-U1 47 - 53	50.00	1	mineral	24.77	1.60	13.82	30.07	frozen	year-round
CH19-U1 53 - 55	54.00	1	mineral	27.82	1.48	14.86	27.03	frozen	year-round

CH19-U1 57 - 62	59.50	1	mineral	26.19	2.54	15.82	34.66	frozen	year-round
CH19-U1 62 - 68	65.00	1	mineral	25.12	4.23	13.96	40.41	frozen	year-round
CH19-U1 70 - 72	71.00	1	mineral	24.83	4.50	17.57	43.88	frozen	year-round
CH19-U5 dung	-8.00	5	NA	28.99	NA	NA	NA	NA	year-round
CH19-U5 vegeta-tion	-3.00	5	NA	2.25	NA	NA	NA	NA	year-round
CH19-U5 fur	-15.00	5	NA	9.70	NA	NA	NA	NA	year-round

(Windirsch et al. 2022, Windirsch et al. 2023)

Although the data for grazing intensities 2 and 4 were not examined in this study, the table above shows a complete data set of the soil cores taken for the Windirsch et al. pilot studies.

APPENDIX C: CORRELATION MATRICES

CORRELATION MATRIX FOR THE PERMAFROST GROUND IN CHERSKY, SIBERIA

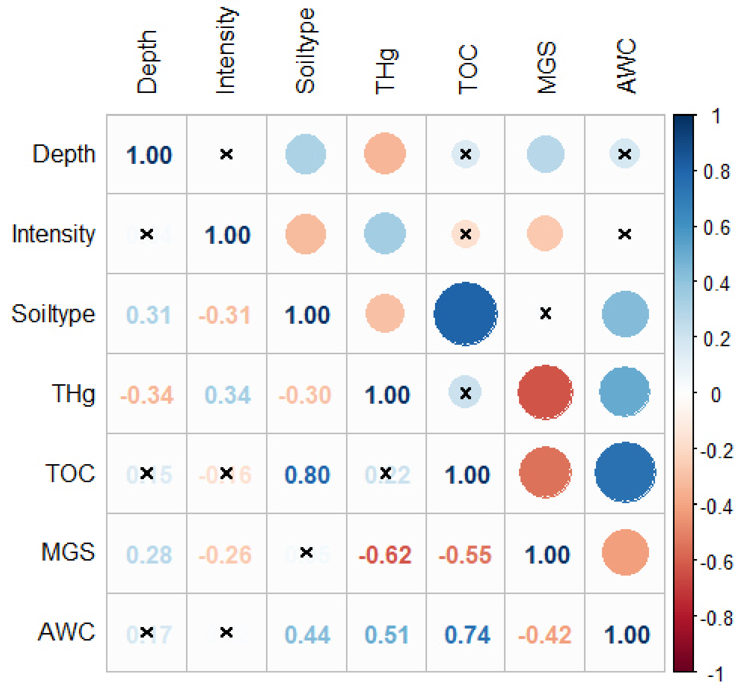

Figure A-1: Correlation matrix of the permafrost ground in Chersky, Siberia. *Intensity and mercury concentration show a positive correlation with a correlation value of 0.34.*

CORRELATION MATRIX FOR THE ACTIVE LAYER OF THE PERMAFROST GROUND IN CHERSKY, SIBERIA

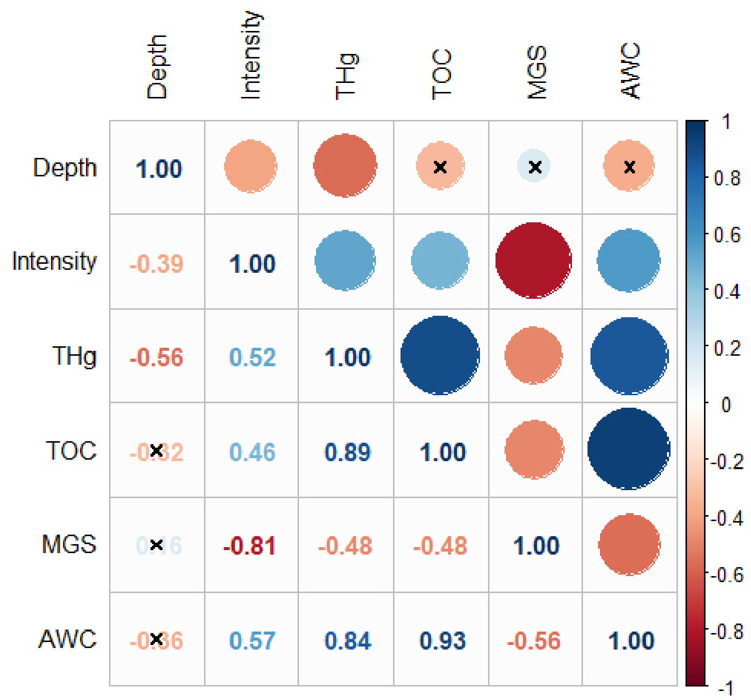

Figure A-2: Correlation matrix for the active layer of the permafrost ground in Chersky, Siberia. *Intensity and mercury concentration show a positive correlation with a correlation value of 0.52.*

CORRELATION MATRIX FOR THE PERMAFROST LAYER OF THE PERMAFROST GROUND IN CHERSKY, SIBERIA

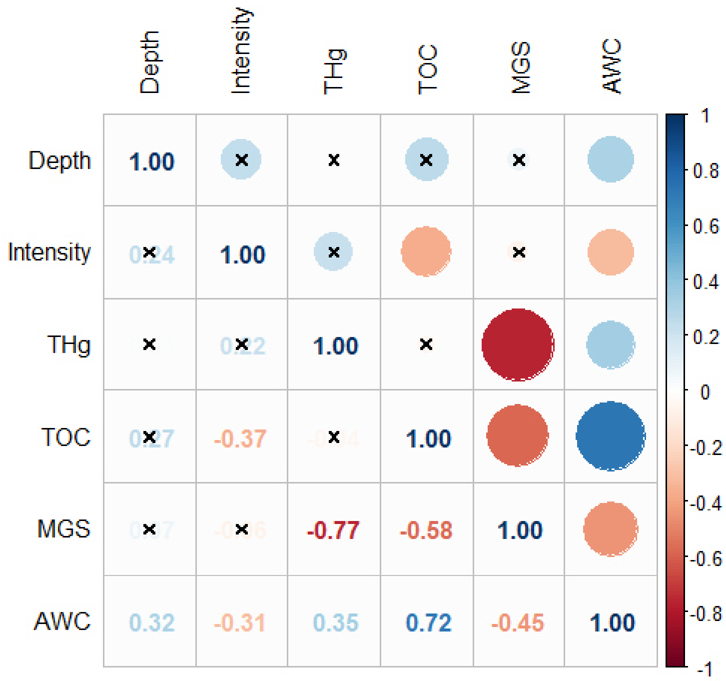

Figure A-3: Correlation matrix for the permafrost layer of the permafrost ground in Chersky, Siberia. Intensity and mercury concentration show no significant correlation.

CORRELATION MATRIX FOR THE SEASONALLY FROZEN GROUND IN INARI, FINLAND

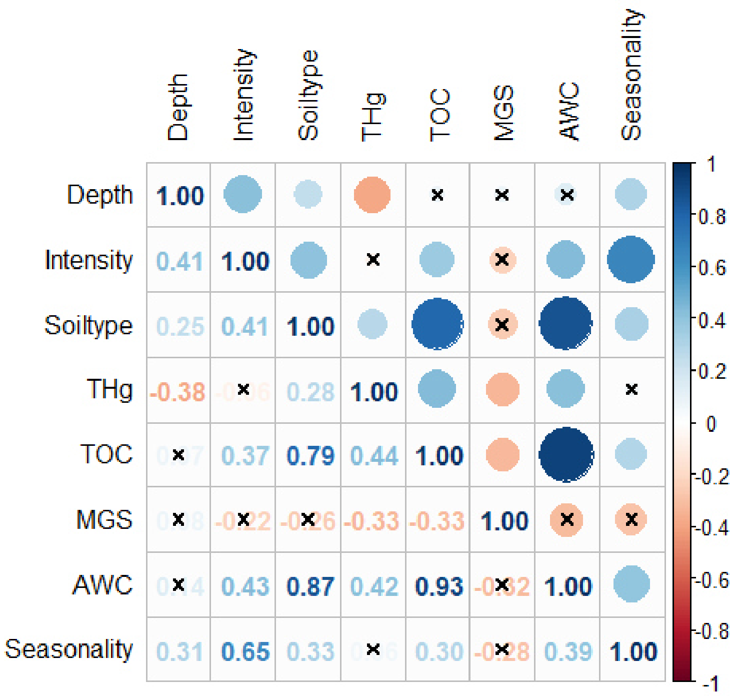

Figure A-4: Correlation matrix for the seasonally frozen ground in Inari, Finland. Intensity and mercury concentration show no significant correlation.

CORRELATION MATRIX FOR THE MINERAL CORES OF THE SEASONALLY FROZEN GROUND IN INARI, FINLAND

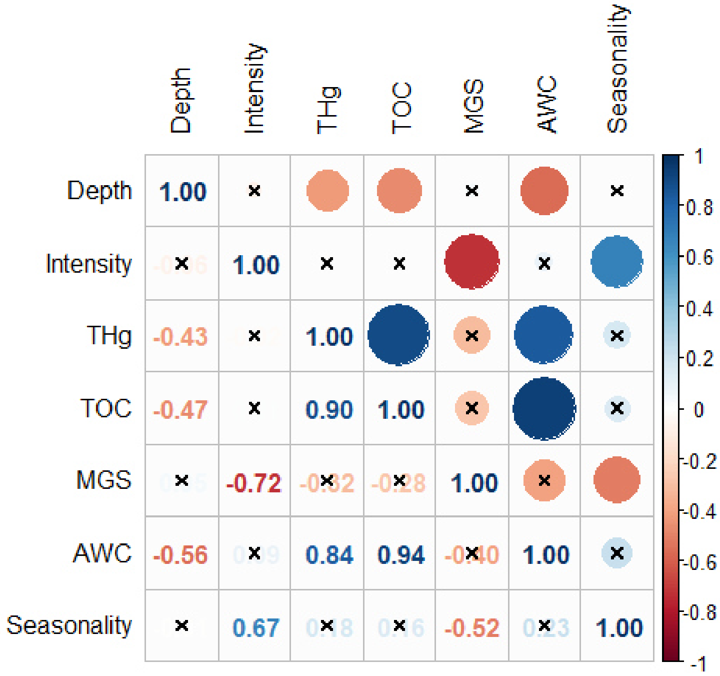

__Figure A-5: Correlation matrix for the mineral cores of the seasonally frozen ground in Inari, Finland.__ Intensity and mercury concentration show no significant correlation.

CORRELATION MATRIX FOR THE PEAT CORES OF THE SEASONALLY FROZEN GROUND IN INARI, FINLAND

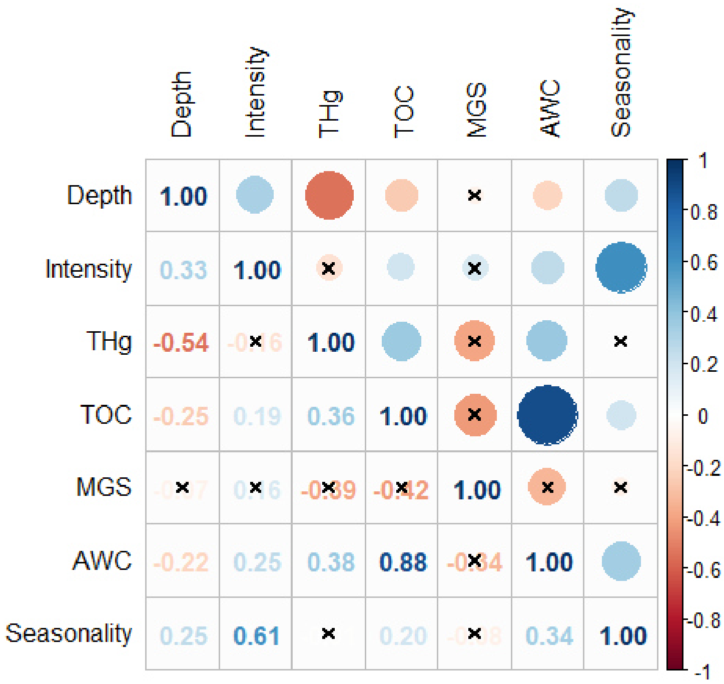

__Figure A-6: Correlation matrix for the peat cores of the seasonally frozen ground in Inari, Finland.__ Intensity and mercury concentration show no significant correlation.

CORRELATION MATRIX FOR THE UPPER 20 CM OF THE MERGED DATA SET

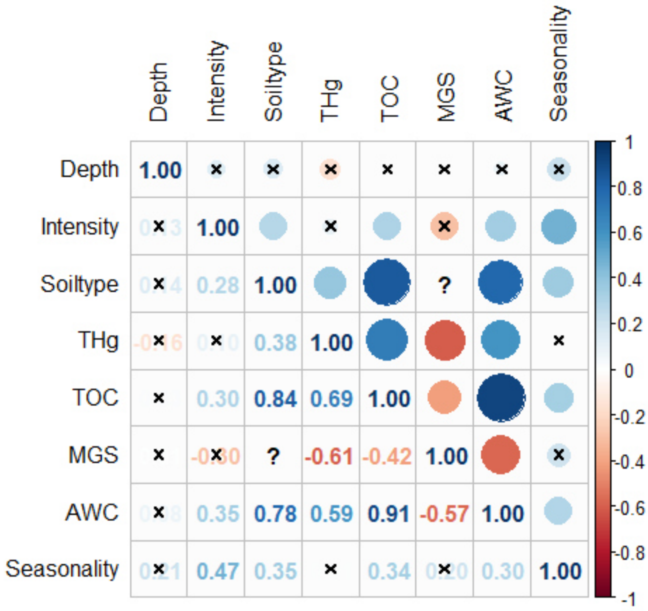

Figure A-7: Correlation matrix for the upper 20 cm of the merged data set. *Intensity and mercury concentration show no significant correlation.*

DECLARATION OF AUTHORSHIP / EIGENSTÄNDIGKEITSERKLÄRUNG

Hiermit versichere ich, Anna-Lena Matzander, dass ich die vorliegende Bachelorarbeit selbstständig und ohne Benutzung anderer als der angegebenen Hilfsmittel angefertigt habe. Die aus fremden Quellen wörtlich oder sinngemäß übernommenen Gedanken sind als solche gekennzeichnet. Diese Arbeit wurde in gleicher oder ähnlicher Form noch keiner anderen Prüfungsbehörde vorgelegt.

I, Anna-Lena Matzander, hereby affirm that I have written this bachelor thesis independently and without the use of any other than the indicated sources. Thoughts and quotes by the cited sources, used either literally or by content, are marked as such. This thesis has not been submitted in the same or similar form to any other examination authority.

Potsdam, den 28.09.2023

A.L Matzander

Anna-Lena Matzander