Mercury storage and methylation in thawing permafrost – a literature review

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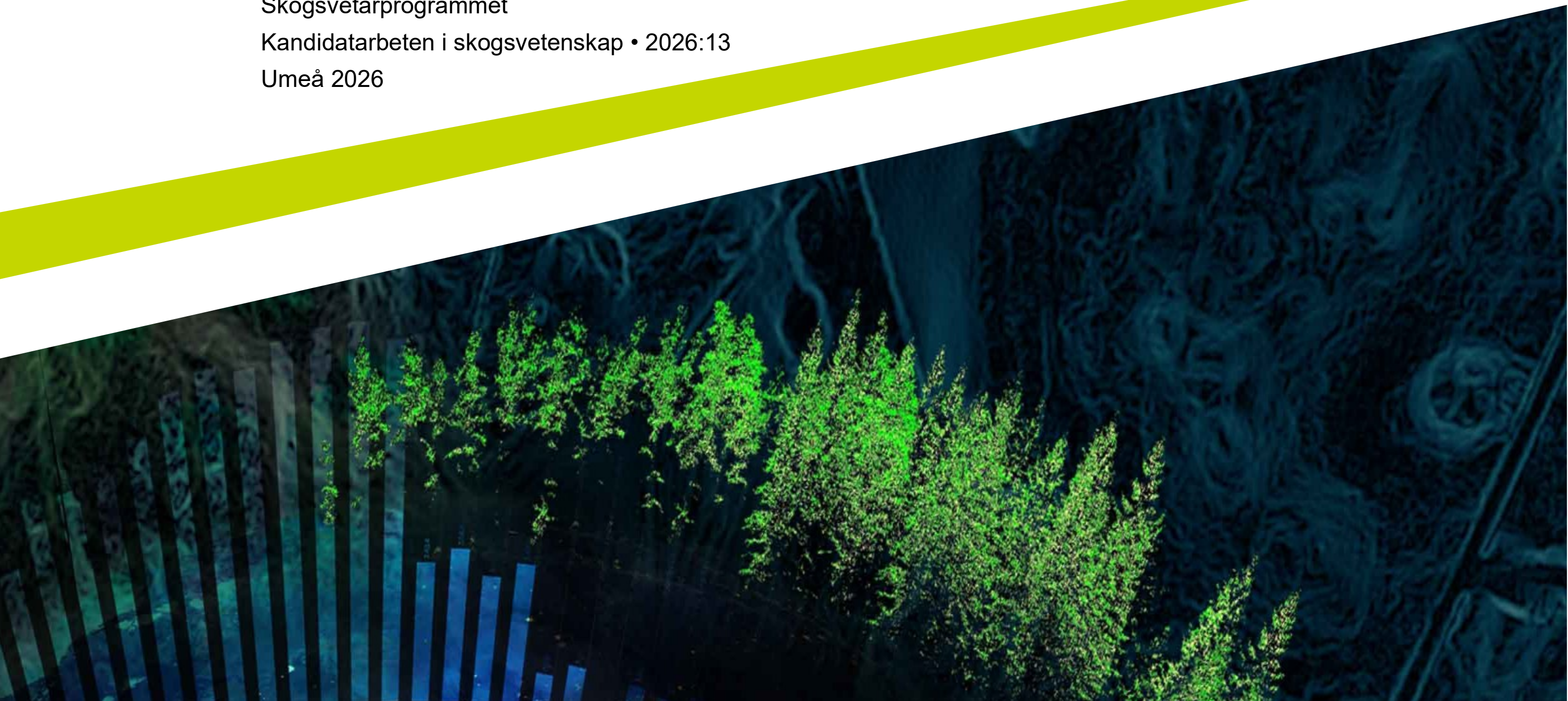

Mercury storage and methylation in thawing permafrost – a literature review.

Kvicksilverförråd och metylering i tinande permafrost – en litteraturstudie.

Ella Hjelm

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Abstract

Mercury (Hg) is a naturally occurring element, but is also regarded as a global pollutant due to its toxicity. Historically, Hg from natural and anthropogenic emissions has accumulated in permafrost, resulting in a significant Hg storage. As global warming proceeds, the permafrost soils thaw and Hg is reemitted back into the atmosphere and its global Hg cycle. The aquatic and anoxic environments arising after thaw promote Hg methylation, resulting in potently neurotoxic methylmercury (MeHg) that easily bioaccumulates in food-webs and poses a threat to both humans and wildlife. There is currently a research gap regarding the exact impacts of permafrost thaw on mercury release, quantity and speciation. To establish a base for future research, this study aims to compile and evaluate the state-of-the-art knowledge on the total amount of Hg stored in permafrost soils and how Hg methylation is impacted by thawing. I conclude that there is indeed a significant amount of Hg stored in permafrost regions, although the exact amounts are debated and regional variabilities are large. Further, permafrost thaw gives rise to landscape level Hg methylation hotspots. The methylation rates are however controlled by several different factors, most importantly dissolved organic matter abundance and chemical composition, nutrient availability, temperature and microbial activity. Mercury methylation is thus a very complex but impactful process, with still remaining research gaps that will need to be resolved.

Keywords: Mercury, Storage, Methylation, Permafrost, Thaw

Sammanfattning

Kvicksilver (Hg) är ett naturligt förekommande grundämne, men anses också vara ett globalt förorenande ämne på grund av dess toxicitet. Historiskt har Hg från naturliga och antropogena utsläpp ackumulerats i permafrost, vilket skapat ett stort kvicksilverförråd. I takt med att den globala uppvärmningen fortskrider tinar permafrosten, vilket leder till att Hg släpps tillbaka ut i atmosfären och dess globala Hg cykel. De akvatiska och anoxiska miljöerna som uppstår efter att permafrosten tinat har hög potential för metylering av Hg, vilket resulterar i produktion av neurotoxiskt metylkvicksilver (MeHg) som lätt bioackumuleras i näringskedjorna och utgör en risk för både människor, fisk och vilt. I dagens läge finns en kunskapslucka kring exakt hur permafrostens tinande påverkar utsläpp och speciering av Hg, samt vilka kvantiteter det rör sig om. För att kunna utgöra en bas för framtida forskning syftar den här studien till att sammanfatta och utvärdera dagens kunskapsläge kring kvantiteterna Hg lagrat i permafrostjordar samt hur metylering av Hg påverkas när permafrosten tinar. Jag drar slutsatsen att det finns en signifikant mängd Hg lagrad i permafrost, även om de exakta kvantiteterna är omdiskuterade och det finns stora regionala skillnader. Tinande permafrost ger dessutom upphov till miljöer med mycket stor potential för metylering av Hg sett till hela landskapet. Metyleringshastigheten påverkas dock av flera olika faktorer, huvudsakligen förekomsten av och den kemiska kompositionen på löst organiskt material, tillgången till näringsämnen, temperatur och mikrobiell aktivitet. Metylering av Hg är därför en komplex och effektfull process innehållande många kunskapsluckor som behöver studeras vidare.

Nyckelord: Kvicksilver, Förråd, Metylering, Permafrost, Tö

Table of contents

List of tables

List of figures

Abbreviations

Hg	Mercury
MeHg	Methylmercury
%MeHg	Proportion of the total amount of Hg that occurs as MeHg
R_{HgC}	The ratio between Hg and carbon (µg Hg/g C)
SOC	Soil Organic Carbon
DOM	Dissolved Organic Matter
DOC	Dissolved Organic Carbon
SRB	Sulphate Reducing Bacteria
IRB	Iron Reducing Bacteria
RCP	Representative Concentration Pathway
IPCC	Intergovernmental Panel on Climate Change

1. Introduction

1.1 Background

Mercury (Hg) is a global pollutant able to travel large distances trough the atmosphere when in elemental gaseous form, Hg^0 (Bravo & Cosio 2020). It is also in the form of Hg^0 the main depositions to the soil occur, in the arctic mostly through dry deposition by plant uptake from the atmosphere (Obrist et al. 2017). Mercury has historically been primarily emitted to the atmosphere as gas through natural processes, such as wildfires (Zolkos et al. 2024) and volcanic eruptions. While weathering of minerals in soils and sediments has been a local contributor, depending on geology (Lindberg et al. 2007). Around the mid-1800s anthropogenic emissions started to increase due to the industrialization and became an important contributor to the global Hg cycle (Lindberg et al. 2007, Rydberg et al. 2010). Historical emissions are also mirrored in the Hg deposition to soils (Rydberg et al. 2010), which has led to a substantial stock of Hg immobilized in permafrost soils that might now be released as soils thaw (Schaefer et al. 2020).

In soils, Hg is primarily present as Hg(II) bound to thiol groups in natural organic matter (Skyllberg et al. 2003). An important process controlling Hg reemission into the atmosphere is reduction of Hg(II) into gaseous elemental Hg^0 (Jiskra et al. 2015, Liu et al. 2000). This can occur either as photoreduction (Amyot et al. 1997) or dark reduction by DOM (Chakraborty et al. 2015, Jiskra et al. 2015). Another central process occurring in aquatic and anoxic environments is microbial methylation of Hg(II), resulting in the production of methylmercury (MeHg) (Hsu-Kim et al. 2013). MeHg is highly neurotoxic and bioaccumulates easily in the food-web, posing a risk to both humans and wildlife (Bravo & Cosio 2020). Thawing permafrost structures, such as thermokarst lakes, can be hotspots for producing the toxic MeHg (Lu et al. 2026), why it is important to study these environments.

A large number of different microorganisms can carry out Hg methylation, such as sulphate reducing bacteria (SRB) (Compeau & Bartha 1985), iron reducing bacteria (IRB) (Kerin et al. 2006), methanogens (Gilmour et al. 2018) and syntrophs (Roth et al. 2021), although there is a high phylogenetic diversity within the groups

(McDaniel et al. 2020). The ability to methylate Hg stems from carrying the hgcAB gene cluster (McDaniel et al. 2020), which makes detection of those genes a common method for investigating the potential of Hg methylation in the environment. Podar et al. (2015) found that the hgcAB gene was present in nearly every anaerobic environment on earth, indicating that Hg methylation can occur almost everywhere if there is a lack of oxygen.

There is currently a research gap regarding the exact impacts of thawing permafrost on mercury release, quantity and speciation. Mercury methylation is a process that increases Hg toxicity and potential for uptake in biota. A review of the state-of-the-art knowledge about this process and the size of the total mercury stock in thawing permafrost could provide an important base for future research.

This study aims to compile and evaluate the state-of-the-art knowledge regarding the total amount of Hg currently stored in permafrost and how permafrost thaw impacts Hg methylation. It is structured around two research questions:

- What is the state-of-the-art knowledge on the total amount of Hg stored in permafrost?
- What is the state-of-the-art knowledge on how Hg methylation is impacted by permafrost thaw?

1.2 Important definitions

In this section, some important definitions that will be used throughout the report are explained:

Thermokarst: According to the Glossary of permafrost and related ground-ice terms thermokarst is defined as "The process by which characteristic landforms result from the thawing of ice-rich permafrost". This includes formations such as shallow thermokarst lakes formed when thawing results in collapsed areas creating depressions in the landscape. (Harris et al. 1988)

Permafrost: Permafrost can be defined in several different ways (Steinert et al. 2023), but scientific articles generally define it as ground that remains at 0°C or below for at least two years. This is also the definition used in the Canadian glossary of permafrost and related ground-ice terms (Harris et al. 1988).

RCPs – Representative Concentration Pathways: Created by IPCC to represent greenhouse gas concentrations in the year 2100 depending on different emission scenarios, based on radiative forcing. Four RCPs exist; RCP 2.6 (least emissions), 4.5, 6.0, and 8.5 (most emissions). These scenarios are used to develop climate projections for possible emission scenarios. (IPCC, 2018)

2. Method

This study was carried out as a literature review. It consisted of two main parts; data gathering (creating a bibliography to base the review on), and reading, summarizing and evaluating the selected articles. Data gathering was primarily conducted using the databases Web of Science and Scopus, since they provide access to an extensive number of peer-reviewed scientific articles.

The primary search terms used were:
- mercury AND permafrost AND storage
- mercury AND permafrost AND methylation

The search terms were varied slightly to decrease the risk of overlooking important sources. The word *permafrost* was substituted with *arctic* and *storage* was substituted with *pool* to broaden the range of the search. Some filtering of the resulting sources was necessary to keep the study manageable. This was conducted by mainly keeping the more recent sources, 2015 and later, although some earlier ones were still used due to their relevancy. Some sources were also excluded after evaluating their abstracts, which sometimes lead to the conclusion that they were not relevant due to focusing on other topics or geographic areas. While reading the selected articles, some additional relevant studies were also found which were not detected in the search. This resulted in a bibliography divided into the two main categories *storage* and *methylation*.

The second part of this study was to read, summarize and evaluate the research communicated by the selected sources. All sources in the *storage* category were read first, notes of research results and methods used were taken and compared with each other. Based on this analysis the *storage* part of the result section was written. The *methylation* part of this study was conducted in the same way, by first reading all relevant sources, taking notes and then writing the section.

3. Results and Discussion

3.1 Literature search

Using the search terms “mercury AND permafrost AND storage” gave 11 results on Web of Science and 15 results on Scopus. Swapping “permafrost” to “arctic” gave 15 results on Web of Science and 25 results on Scopus. When “storage” was swapped to “pool” the search on Web of Science gave 19 results while Scopus gave 12 results. From these searches, a total of 14 articles were chosen based on the principal of relevance.

When searching for studies on Hg methylation in thawing permafrost soils the search terms “mercury AND permafrost AND methylation” were initially used. This gave 41 results on Web of Science and 40 results on Scopus. Swapping “permafrost” to “arctic” increased the results to 106 on Web of Science and 105 on Scopus. A total of 26 articles were finally chosen from these results.

The remaining 19 sources were found through references within other articles.

3.2 Hg storage in the northern circumpolar permafrost region

3.2.1 Estimates of the total amount of Hg stored in permafrost soils.

Three recent studies have estimated the total amount of Hg stored in the northern circumpolar permafrost region, Schuster et al. (2018), Olson et al. (2018) and Lim et al. (2020). The first two both sampled soils in Alaska, while Lim et al. (2020) sampled soils in Western Siberia. These three studies show rather large differences in their estimates of Hg storage. Schuster et al. (2018) presents the largest Hg pool, while Olson et al. (2018) presents the smallest (Table 1).

All three studies, Schuster et al. (2018), Olson et al. (2018) and Lim et al. (2020), use the same general method when estimating the Hg pool. It consists of first estimating representative R_{HgC} values that are then multiplied with the northern hemisphere carbon pool, estimated by Hugelius et al. (2014). There are also some differences in methodology, mainly regarding the datasets used when estimating R_{HgC}. Schuster et al. (2018) used data from 13 permafrost soil cores along a north-south transect in Alaska. The median R_{HgC} was calculated from these cores and then compared to 11000 previously published data points from permafrost-, boreal- and temperate sites to ensure representativeness. Olson et al. (2018) used data from several different sites in Alaska, mainly located between Toolik field station and the northern coast of Alaska. That data was then combined with data from 14 other studies in the Arctic, resulting in an average R_{HgC} for the upper 30 cm (regarded as organic soil) and another for 30 - 100 cm depth (regarded as mineral soil). Lim et al. (2020) used data from 6 peat cores along a 1700 km north to south transect through the Western Siberian Lowland, combined with the data collections from Schuster et al. (2018) and Olson et al. (2018), covering Russia, Scandinavia, Canada and Alaska. Based on this, an average R_{HgC} was calculated for organic- and mineral soils. These differences in methodology are likely the main cause behind the large deviations between the estimates of the total Hg pool.

Table 1. Estimates of the total amount of Hg stored in soils in the northern circumpolar permafrost region. The uncertainties of the estimates by Schuster et al. (2018) are not clearly presented in the article, but are most likely ± 37,5th - 62,5th percentile.

Study	0-30 cm (Gg)	0 – 100 cm (Gg)	0 – 300 cm (Gg)	Uncertainties
Schuster et al. (2018)	347 ± 196	755 ± 427	1656 ± 962	Median ± 37,5th - 62,5th percentile
Olson et al. (2018)	26 (21 - 42)	184 (136 - 274)	-	Median (37,5th - 62,5th percentile)
Lim et al. (2020)	72 (39 - 91)	240 (110-336)	597 (384 - 750)	Median (25th to 75th percentile)

Estimates of the total amount of Hg stored in the northern circumpolar permafrost region have been made for three soil depths, 0 - 30 cm, 0 - 100 cm and 0 - 300 cm. For the upper 30 cm, The Schuster et al. (2018) estimate was about five times higher than the estimate of Lim et al. (2020), and about ten times higher than the one of Olson et al. (2018). For the 0 - 100 cm depth-interval, the estimate by Schuster et al. (2018) was about three times higher than the one of Lim et al. (2020) and about four times as high as the one reported by Olson et al. (2018). Olson et al. (2018) did not report any estimate for the 0 - 300 cm depth-interval, but the estimate of Schuster et al. (2020) was once again about three times higher than the estimate by Lim et al. (2020). These estimates are also reported in Table 1. It is worth noting that the uncertainties associated with these values are substantial, meaning that even though the differences seem large, most still overlap.

The estimate of the total amount of Hg stored in the northern hemisphere permafrost region by Schuster et al. (2018) is often referred to as an undisputed truth, for example by Fahnestock et al. (2019), Wenwen et al. (2023) and Gambardella et al. (2025). As is evident by my comparison here, there exists at least two other studies (Lim et al. 2020, Olson et al 2018) presenting estimates that differ largely from the one by Schuster et al. (2018).

Table 2. The R_{HgC} values used when estimating the amount of Hg stored in permafrost regions. Schuster et al. (2018) used one value for the total estimation. Olson et al. (2018) used one value for the upper 30 cm of soil, which was regarded as organic, and one value for 30 – 100 cm depth regarded as mineral soil. Lim et al. (2020) also used two values, one for organic soils and one for mineral soils.

Study	R_{HgC} µg Hg/g C
Schuster et al. (2018)	1,6 ± 0,9 *(Median ± 25th to 75th percentile)*
Olson et al. (2018)	0 - 30 cm: 0,274 30 - 100 cm: 0,621
Lim et al. (2020)	Organic = 0,19 Mineral = 0,63

Generally, the R_{HgC} values (Table 2) correspond well to their respective estimate of the Hg stock, meaning that the largest R_{HgC} resulted in the largest estimated Hg stock. There is one exception though, the R_{HgC} value of 0,274 µg/g for 0 - 30 cm (organic soil) by Olson et al. (2018). This value corresponds to the lowest estimate of Hg stored in the upper 30 cm, although Lim et al. (2020) used a lower R_{HgC} value for their estimate of the same Hg stock. Since all three studies are based on the global carbon estimate by Hugelius et al. (2014), the lowest R_{HgC} value will by necessity result in the lowest Hg storage estimate. This discrepancy is also pointed out by Lim et al. (2020) as a typo, they state that the R_{HgC} value used by Olson et al. (2018) was 0,119 µg/g instead of 0,274 µg/g, which would make the Hg estimate correspond better to its respective R_{HgC}. There is however no further proof that the R_{HgC} value 0,274 µg/g indeed is a typo in Olson et al (2018).

To further compare R_{HgC} values and total Hg estimates, the study by Lim et al. (2020) is of relevance. They estimated R_{HgC} values for both the Western Siberian Lowland (WSL) and the whole northern circumpolar permafrost region. The R_{HgC} for WSL was estimated to 0,13 ± 0,12 µg/g, which is lower than their global R_{HgC}

for both the organic- and mineral soils in permafrost (Table 2). This suggests that Siberia contains lower amounts of Hg in permafrost soils than the rest of the world, which would lead to an overestimation of the global stock if not taken into consideration. Schuster et al. (2018) mainly used data from North America, meaning that they might not have considered the reported lower Hg amounts in Siberia. This could explain why their reported estimate is so much higher than the reports by Olson et al. (2018) and Lim et al. (2020).

The lowest estimates of Hg stored in the northern circumpolar permafrost region is consistently reported by Olson et al. (2018). Their definition of the area for which the estimates were considered representative also differed slightly from the other two studies (Schuster et al. 2018 and Lim et al. 2020), by focusing on tundra rather than permafrost. They (Olson et al. 2018) also restrict themself to the active layer, reckoned as the upper 100 cm, which is why no estimates at depths below 100 cm is provided. This depth-limitation does on the other hand also indicate that their estimate of the Hg pool still considers permafrost soils. Focusing on tundra instead of permafrost could however mean that the estimate by Olson et al. (2018) considers a different geographic area than the other two studies (Schuster et al. 2018 and Lim et al. 2020), which could contribute to why it is the lowest of the three.

Even though these studies present very different estimates of the total amount of Hg stored in permafrost regions, all of them demonstrate that pools of Hg in permafrost regions are significant. The large variation among the results and their rather large uncertainties (Table 1) highlights the need for further studies using R_{HgC} data that considers regional variations, possibly by establishing different R_{HgC} values adapted to specific regions.

3.2.2 Mercury concentrations in permafrost soils of various geographic regions and impacting factors

Information about the global Hg stock in permafrost can be won by the Hg concentrations reported for permafrost of certain geographic regions. In this section a selection of such studies from a wide geographic range is presented, together with some studies on Hg export from thawing permafrost.

Table 3. Reported Hg concentrations and the factor R_{HgC} in permafrost regions from a selection of studies covering different geographic areas globally.

Study	Geographic location	ng Hg/g soil	R_{HgC} µg Hg/g C
Gu et al. (2020)	Tibetan plateau	19,8 ± 12,2	5,6 ± 6,5
Klaminder et al. (2008)	Northern Sweden (Stordalen mire)	Hummocks: 70 - 200 Hollows: 40 - 112	-
Olson et al. (2018)	Alaska (Toolik field station)	Organic soil: 151 ± 7 A horizon: 108 ± 10 B horizon: 87 ± 5	0 - 30 cm: 0,274 30 - 100 cm: 0,621
Peña-Rodríguez et al. (2014)	Southern Argentina (Tierra del Fuego)	12 - 375 (mostly below 100)	1 – 11,3 (Increase with depth)
Schuster et al. (2018)	Alaska	43 ± 30	1,6 ± 0,9
Xin et al. (2021)	China (Greater Khingan Mountains Wetlands)	60 - 190	-
Lim et al. (2020)	Western Siberia	67 ± 57	Organic soil: 0,19 Mineral soil: 0,63
Cardinal et al. (2025)	Canada (Northern Quebec)	68	Median: 0,34 Mean: 0,73

Table 3 shows the results of a selection of studies from different parts of the world investigating Hg concentrations and R_{HgC} in permafrost areas. It is evident that the Hg concentrations vary greatly among sites and different soils, with values ranging from below 5 ng/g up to over 300 ng/g. Most measurements involve high uncertainties, further highlighting the variability. The majority of the values in Table 3 are within the range of about 20 to 150 ng/g though, and all measurements fall within this range when considering their uncertainties. Further, the R_{HgC} values differ largely between study sites and soil properties, once again highlighting the substantial uncertainties regarding large scale Hg stock estimates based on this parameter.

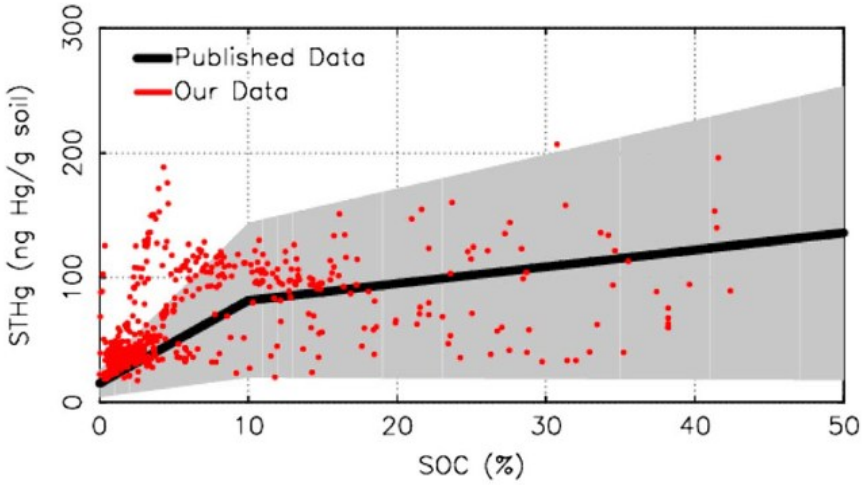

Figure 1. The concentration of Hg in permafrost soil as a function of the percentage soil that consists of organic carbon (SOC). Grey areas represent the 90% envelope of 11000 previously published data points and the black line is the median of these values, red dots represent data recorded by Schuster et al. (2018) in Alaska. The correlation between STHg and SOC (black line) for SOC<10% has an R^2 = 0,98, the R^2 for SOC>10% is 0,56. Figure from Schuster et al. (2018) page 5.

Some parameters have been found to impact the Hg concentration in soils, one of them is the soil organic carbon content (Klaminder et al. 2008; Olson et al. 2018; Schuster et al. 2018; Gu et al. 2020, Cardinal et al. 2025). Schuster et al. (2018) found a strong correlation between soil organic carbon (SOC) and Hg concentration (Figure 1) with an R^2 of 0,98 at SOC<10%. This correlation decreased to R^2 = 0,56 at SOC>10%. Schuster and co-workers reasoned that this difference in correlation shows a switch of the main factor limiting Hg concentration around SOC=10%. They suggest that the Hg concentration is mainly limited by the amount of receptor sites on the SOC available for Hg to bind at SOC<10%. When these sites become more abundant (SOC>10%) the Hg concentration is instead limited by atmospheric Hg influx (Schuster et al. 2018). This explanation does however seem rather unreasonable since the abundance of thiol-groups available for Hg to bind to is always much higher (>1000 times) than the Hg concentration even in soils with less than 1% SOC, meaning that Hg can never be limited by the availability of binding functional groups of organic matter in soils (Skyllberg et al. 2003). The phenomenon instead likely has a statistical explanation. The relative increase in SOC at low %SOC is much higher than at higher %SOC. For example there is a 100% increase between 1-2% SOC but only 50% increase between 20-30% SOC. Thus, because Hg is bonded to SOC, the concentration of Hg strictly follows SOC when the latter is diluted into a large proportion of mineral matter in low %SOC soils. However, when SOC is making up a larger proportion of the soil, the type of organic matter (more degraded SOC contains higher concentrations of Hg and less degraded litter contains less) is making more of a difference and the relationship between Hg and SOC breaks down. The impact of the heterogeneity of SOC, and its content of Hg thus increases with rising %SOC, meaning it is highly unlikely to find correlations.

There is clearly a strong correlation between SOC and Hg content, all depending on the range of %SOC in the population of data investigated. The wider %SOC range the stronger the correlation, of statistical reasons. Gu et al. (2020) found a correlation (R^2 = 0,36) between Hg concentration and SOC in the top 50 cm soil. Even stronger relationships between SOC and Hg concentration were reported by Klaminder et al. (2008) with an R^2 of 0,69, Peña-Rodriguez et al. (2014) with an R^2 of 0,821, Cardinal et al. (2025) with an R^2 of 0,72 and Olson et al. (2018) who found that buried organic horizons (due to cryoturbation) had a 15% higher Hg concentration than the surrounding mineral soil.

Mercury content has also been found to decrease with soil depth (Peña-Rodriguez et al. 2014; Schuster et al. 2018; Klaminder et al. 2008; Olson et al. 2018; Kirkwood et al. 2021), with the exception of some occasional subsurface peaks observed by Peña-Rodriguez et al. (2014). Klaminder et al. (2008) mainly attributed the decrease with depth to changes in Hg deposition over time. This is supported by Rydberg et al. (2010) who created a historical deposition record for the area that Klaminder et al. (2008) studied. It showed a quite stable historic deposition with an increase during the industrialisation in the 1800s, the high deposition continued up until the 1970s when a decreasing trend began (Rydberg et al. 2010). In soils with low or variable amounts of SOC the decrease of Hg with depth can also be linked to a similar trend in SOC (Olson et al. 2018).

Also, anthropogenic Hg pollution can impact soil Hg concentrations greatly (Rydberg et al. 2010; Lyapina et al. 2009, Gu et al. 2020). This is evident by the historical records reported by Rydberg et al. (2010), and an increased amount of Hg at the southern Tibetan plateau compared to the northern side, which is further from Hg emission sources in Southern as compared to Northern Asia (Gu et al. 2020). Another example is an area near Tomsk, Russia, affected by pollution from nearby industries. Soils exhibited Hg concentrations in the range 300 – 2250 ng Hg/g soil, which can be compared to the much lower concentrations in areas less affected by Hg pollution (Lyapina et al. 2009) (Table 3). Observations like these highlight the impact anthropogenic Hg sources can have on Hg concentrations in soils.

There are some contradictory reports on the impact by latitude. Lim et al. (2020) found a northward increase in soil Hg concentration across western Siberia, but did not provide any possible explanations. Klaminder et al. (2008) discussed the impact of peat accumulation rates on soil Hg concentration, where a higher rate leads to lower concentrations due to a dilution effect. Provided that productivity and thereby peat accumulation rate decreases further north, this might at least partly explain the observation by Lim et al. (2020). A similar northward increase in Hg concentrations was found by Thompson et al. (2023a), in western Canadian waterbodies. The opposite trend, a northward decrease of Hg concentration, was found by Olson et al. (2018) in northern Alaska, despite a northward increase of organic carbon concentration. They speculate that the trend might be due to lower productivity further north decreasing Hg input from the atmosphere by deposition to vegetation, an argument that opposes the previous explanations for the trend in Lim et al. (2020). It is also important not to forget the possibility of geographic differences in the impact of anthropogenic Hg sources, as observed by Gu et al. (2020).

3.2.3 Potential Hg export from thawing permafrost

To conclude this chapter there is also something to be said about mercury export from thawing permafrost soils. Rydberg et al. (2010) found that although Hg accumulation rates in the peat of Stordalen mire (Sweden) has decreased since the 1970s, the accumulation rate started to increase in nearby lake sediments in the 1990s. This correlates with an increased depth reached by the thawing process, resulting in more runoff export of Hg and carbon to the nearby lake. Klaminder et al. (2008) studied the same area as Rydberg et al. (2010) and observed that when pieces of thawing peat are deposited into hollows it partly dissolves and loses stored Hg together with organic material into the water column, increasing the ability for Hg to be transported away from its long-term storage.

In some studies, the extent of future permafrost thaw and subsequent Hg losses have been estimated. Koven et al. (2013) estimated a permafrost thaw of 15-86% for RCP 4,5 and 30-99% for RCP 8,5 up to the year 2100 using CMIP5 Earth System Models. Schaefer et al. (2020) estimated the thaw in year 2300 to a 29% loss of the top three meters of the global permafrost for RCP 4,5 and a loss of 84% for RCP 8,5. This resulted in an estimated contribution of 101±57 Gg and 428±244 Gg Hg respectively to the global Hg cycle (based on the global Hg stock estimate by Schuster et al. (2018)). Schaefer et al. (2020) also modelled Hg emissions from current permafrost areas to the atmosphere. By the year 2200 global net emissions from thawed permafrost were estimated to 1,9±1,1 Gg Hg/year for RCP 8,5, which is similar to the current global anthropogenic emissions of 2 Gg Hg/year. For RCP 4,5 the net emissions were estimated to 0,5±0,3 Gg Hg/year (Schaefer et al. 2020). Even though these predictions contain large uncertainties there is clearly a risk of extensive permafrost thaw, resulting in organic matter degradation and Hg release.

3.3 Mercury methylation

3.3.1 Mercury methylation along thaw gradients

Several studies have investigated the effect on Hg methylation by permafrost thaw, through studying gradients from frozen soil to thawed structures, such as fens and thermokarst ponds (Cardinal et al. 2025, Fahnestock et al. 2019, Tarbier et al. 2021, Thompson et al. 2025, among others). Mercury methylation has in most cases been found to increase when the soil changes from frozen to thawed conditions. Cardinal et al. (2025) reported an increase in %MeHg from 0,57% in the active layer of a frozen lithalsa (mineral dominated soil that has been raised through the formation of an underground ice lens) to 4,6% in adjacent thermokarst depressions. Similar trends have been reported by Fahnestock et al. (2019) who found increasing soil concentrations of MeHg along a thaw gradient. Gordon et al. (2016) demonstrated highly increased %MeHg and MeHg concentrations in newly thawed fens and Tarbier et al. (2021) recorded 13 times higher %MeHg in a thawed fen, as compared to the active layer of the nearby frozen peat.

Mercury methylation rates in previously frozen areas have been shown to not only be higher than in still frozen soils, but also compared to soils and waters outside of the thermokarst landscape (Lu et al. 2026, MacMillan et al. 2015). Lu et al. (2026), for example, reported %MeHg to be one order of magnitude higher in thermokarst lakes than in nearby reference waters and they found about three times as high %MeHg in thermokarst lake sediments compared to reference soils. This supports the notion that thawing permafrost indeed gives rise to Hg methylation hotspots at the landscape level.

There are of course also some opposing observations to the Hg methylation trend described above. An experiment to induce thawing was carried out by Haugk et al. (2026) using fences to accumulate snow and thereby isolate part of a permafrost peatland during the coldest period of winter. After 17 years of induced thawing ponds were formed in five of six test plots. There were no differences in total Hg, MeHg or %MeHg as compared to the frozen control plot. This could however be the result of a more gradual and incomplete thaw than in for example the collapsed fens studied by Tarbier et al. (2021). Haugk et al. (2026) also state that permafrost likely still was present deeper into the soil, meaning that it might have been too early for any significant change in Hg methylation to occur. This is further supported by the fact that the thawed areas in Gordon et al. (2016) were about 50 years old and Cardinal et al. (2025) studied some areas that were already thawing in the 1960s.

Another interesting observation was made by Cardinal et al. (2025) regarding Hg methylation and time since thaw. The %MeHg was found to be highest closest to the thaw edge and decreased with successional stage as the thaw ponds were colonized by plants and finally *Sphagnum* mosses. This trend does also coincide with a change from a wet and anoxic environment devoid of plants in the newly thawed fens to a more oxygenated environment with more nutrient demanding plants, which could explain the decreased Hg methylation. Tarbier et al. (2021) drew the same conclusion, that the rates of Hg methylation are highest in newly thawed fen environments and then decreases with age until a stable level is reached. Although this also likely depends on what characteristics (oxic or anoxic, plant species, etc.) the wetlands develop as time goes on.

If the successional thawing gradient from anoxic to more oxygen rich environments is common, the finding by Cardinal et al. (2025) implies that increased methylation during permafrost thaw may be a short-term problem. On the other hand, Sun et al. (2024) reasoned that warming will introduce more vegetation into previously frozen areas, potentially increasing Hg uptake/deposition from the atmosphere. Such a vegetation shift was also found by Wenwen et al. (2023) who reported varying Hg methylation rates in wetlands dominated by forest, shrubs, mosses or herbs. The exact impacts of vegetation change have however not yet been extensively studied, so it is difficult to determine how a long-term vegetation shift in thermokarst landscapes would influence Hg methylation.

3.3.2 Biogeochemical factors impacting Hg methylation in thawing landscapes

Thawing permafrost releases Hg (Fahnestock et al. 2019), DOM (Rydberg et al. 2010) and increases the abundance of components such as sulphate, iron (Fe) and nitrogen (N) (Roth et al. 2021). The resulting environments are often waterlogged, with reducing conditions favourable for Hg methylation (Cardinal et al. 2025). The Hg methylating microbial community is generally favoured by these conditions and increases in abundance and diversity after permafrost thaw (Roth et al. 2021). In this section, the effect of these biogeochemical factors on Hg methylation are further investigated.

Mercury methylation and the microbial community composition have often been found to correlate with nutrient abundance (Tjerngren et al. 2012, MacMillan et al. 2015, Roth et al. 2021). This means that the Hg methylation potential differ between thermokarst structures of different trophic status (Poulin et al. 2019). Fens generally exhibit higher methylation rates than ombrotrophic bogs, Gordon et al. (2016) did for example find between 4 to 17 times higher concentrations of MeHg in waters coming from poor fens than from bogs located in the same thermokarst landscape. Observations by Poulin et al. (2019) also support the notion that poor fens are Hg methylation hotspots. They found the highest %MeHg (indicating high net methylation rates) in poor fens of intermediate trophic status compared to bogs and rich fens. Tjerngren et al. (2012) observed the same phenomenon, that wetlands of low and intermediate trophic status had the highest net methylation rates. Thompson et al. (2025) agrees that nutrient poor bogs exhibit low methylation rates, but found higher net Hg methylation in rich fens than poor fens. These inconsistencies clearly indicate that factors other than trophic status may impact Hg methylation as well.

The microbial community can also be affected by nutrient availability. Roth et al. (2021) investigated how the Hg methylating microbial community changed along a nutrient gradient in a subarctic fen. They found increased abundance and diversity of Hg methylating organisms and high %MeHg where the nutrient source was located, followed by a decrease in all parameters with distance from the source. However, Thompson et al. (2025) didn't find any correlation between nutrient availability and microbial abundance or diversity when comparing thermokarst fens, bogs and peat plateaus. The Hg methylation rates and thereby the microbial activity was still highest in the nutrient rich fens though, agreeing with the methylation rates observed by Roth et al. (2021). This indicates that a high abundance of Hg methylating microorganisms can, but doesn't necessarily correspond to high Hg methylation rates, it's the microbial activity that really matters.

The microbial activity also increases with warming and subsequent thawing of permafrost. This has been seen through increased metabolic activity resulting in production of MeHg, CH_4, CO_2, Fe(II) and corresponding loss of substrates such as the electron acceptor Fe(III), the methylation substrate Hg(II) and degradation of SOC and DOM, affecting the electron-donors for methylating microbes, when temperature increases (Wenwen et al. 2023, Yang et al 2016). Warming thus both leads to increased substrate availability and microbial activity, both increasing the Hg methylation potential.

DOM composition and abundance is another factor that has been found to impact Hg methylation in the thermokarst landscape (Sun et al. 2024, Gindorf et al. 2025, among others). The quality of DOM is expected to mainly affect the electron-donation required for the metabolism of anaerobic, Hg methylating microbes (Zhao et al. 2017, Bravo & Cosio 2020). As soils heat up and permafrost thaws due to global warming, microbial activity increases and leads to decomposition and mineralization of SOM that is subsequently released as DOM (Sun et al. 2024).

Mercury methylation has generally been found to correlate with the presence of aromatic, humic DOM (Gordon et al. 2016, Thompson et al. 2023b, Martins et al. 2025, among others). Degradation of DOM is part of the metabolic pathway of many microorganisms, for example methanogens (Zhou et al. 2026). The most easily degradable components, such as carbohydrates and protein-like substances, are utilized first as electron donors which makes the concentration of recalcitrant aromatic and humic-like substances increase as degradation progresses (Xu & Guo 2018). Therefore, the correlation between aromatic, humic DOM and MeHg is likely the cause of microbes having used Hg(II) and the more easily degradable components in DOM in their metabolism. Not that the actual presence of humic DOM increases methylation rates. High abundance of less degraded labile DOM has however been found to increase methylation, likely due to the easily degradable compounds still being available (Thompson et al. 2025).

DOM quality and abundance can also impact the chemical properties and bioavailability of Hg. A positive correlation between DOM and Hg concentrations has often been found (Wu et al. 2022, MacMillan et al. 2015, among others), but the relationship between DOM and MeHg varies more. Negative relationships between DOM and %MeHg (percentage of total Hg) were observed by Haugk et al. (2026), and Wu et al. (2022) found differences in %MeHg depending on if the DOM was autochthonous (higher %MeHg) or allochthonous (lower %MeHg). Bravo et al. (2017) also found higher methylation rates in lakes dominated by autochthonous DOM, but the total concentrations of Hg and MeHg were higher when allochthonous DOM dominated due to transport from the catchment area. This study was however carried out in boreal lakes, meaning the observations might not apply perfectly to the permafrost landscape. Schaefer et al. (2011) connected higher Hg methylation rates to the presence of small thiols in the DOM, due to these Hg-thiol complexes being highly bioavailable to Hg methylating microorganisms compared to larger and more branched ones. These different observations make it clear that methylation of Hg is indeed as Bravo & Cosio (2020) concluded; “A bio-physico-chemical conundrum”.

Some solutes can both inhibit and promote Hg methylation. Zhang et al. (2023) found that Hg methylation by SRB and methanogens was inhibited by the presence of nitrous oxide (N_2O). On the other hand, Sun et al. (2024) observed a positive correlation between MeHg and N, which further highlights the importance of chemical composition and not only the presence of chemical compounds. Sulphur (S) is also an ambivalent compound regarding Hg methylation. Higher concentrations of S compounds can inhibit Hg methylation by forming the insoluble precipitate HgS (s) (Lu et al. 2026, Skyllberg et al. 2003, Gilmour et al. 2018), thus decreasing the amount of bioavailable Hg. Sulphate is however also an important substrate for Hg methylating SRB, and has been shown to increase methylation rates when added (Branfireun et al. 2001). Furthermore, S can as previously discussed increase the bioavailability of Hg to methylating microorganisms when in the form of small thiols (Schaefer et al. 2011).

Another important effect of Hg methylation can be the release of greenhouse gases. Methane is for example produced by methanogens during Hg methylation (Gilmour et al. 2018) and correlations between MeHg, CO_2 and CH_4 have been found by Wenwen et al. (2023), Yang et al. (2016) and Campeau et al. (2025) among others. This indicates a possible positive feedback loop during permafrost thaw. When Hg methylation hotspots arise from the thaw, greenhouse gases are produced along with MeHg which in turn further increases the global warming and permafrost thaw. It is however unclear as to what extent the Hg methylation process would increase greenhouse gas emissions since Hg methylation rates are so much lower than for example CH_4 production from other sources, questioning whether it would have any real impact.

The observations evaluated in this chapter highlight that the physical structures arising from permafrost thaw vary largely in chemical and biological structure and composition. It is also clear that these properties greatly impact Hg methylation, although they are not always well understood. It is also worth noting that most studies investigating Hg methylation and the impacting factors have been conducted in boreal or marine environments, not in thawing permafrost landscapes. This means that the uncertainties regarding the impact of permafrost thaw on Hg methylation are still rather large and that more studies should be conducted in these environments.

3.4 Conclusion

Mercury storage and speciation in permafrost is a complex topic, currently containing large uncertainties. Permafrost regions store substantial amounts of Hg, which may be released as permafrost thaws under ongoing climate warming. The magnitude of this Hg stock and potential release varies regionally, depending on factors such as SOC content and historical Hg deposition. These regional differences add a major source of uncertainty in current estimates of total Hg stocks in permafrost environments. In addition to mobilizing stored Hg, permafrost thaw gives rise to landscape level Hg methylation hotspots. Extensive Hg release combined with increased methylation has the potential to contribute significant amounts of toxic MeHg to aquatic ecosystems, posing a threat to both humans and wildlife. However, the extent of Hg methylation depends on several different environmental factors, such as natural organic matter abundance and composition, nutrient availability, temperature and microbial activity, meaning local variability is large.

It is also important to consider the processes that influence the fate of Hg following methylation. This includes potential demethylation, reduction of Hg(II) to gaseous elemental mercury (Hg^0), and hydrological connectivity within the landscape, which determines whether MeHg is transported to surrounding ecosystems or retained locally. These processes clearly need to be further studied, particularly since much of the existing research has been conducted in marine and boreal regions and might not apply perfectly to permafrost environments.

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