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Permafrost thaw remobilizes mercury from northern Scandinavian peatlands

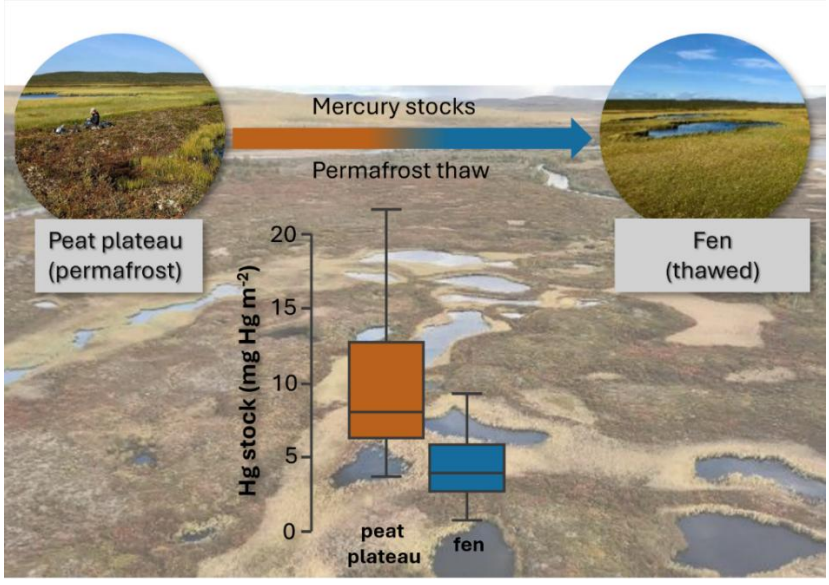
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Abstract. With ongoing Arctic warming, mercury (Hg) stored in permafrost peatlands is at risk of being remobilized as permafrost thaws due to ground subsidence, peat inundation and enhanced decomposition of organic matter. Once released, Hg may enter the pool available for microbial Hg methylation to the neurotoxic methylmercury (MeHg), which bioaccumulates in food webs and poses health concerns to northern communities and wildlife. Whether and to what extent Hg is remobilized from northern permafrost peatlands following thaw, however, remains poorly understood. Here, we collected 93 peat cores from five permafrost peatlands in Norway and Sweden from landforms representing intact and thawed conditions (peat plateaus/palsas and fens, respectively) to investigate Hg dynamics in sub-Arctic thawing permafrost peatlands. We found consistently lower Hg stocks in thawed features across all investigated sites, with median values of 5 mg Hg m^{-2} in fens and 10 mg Hg m^{-2} in peat plateaus. The lower stocks of Hg were a result of both lower concentrations of Hg in surface peat as well as overall lower peat mass of the fens, suggesting both organic matter degradation and Hg leaching from peat to play a role for Hg remobilization after thaw. Our study highlights the importance of accounting for landscape heterogeneity when studying Hg dynamics in permafrost peatlands. Hg concentrations and dry bulk density exhibited moderate variability, whereas carbon content remained relatively consistent throughout the peat profile. Given the landscape variabilities demonstrated with our data (e.g. peat depths), the large number of peat cores and within-core Hg measurements in this study supports our conclusion that Hg is lost from the peat matrix upon thaw. From Swedish and Norwegian permafrost peatlands alone (area of 130 km^2), we estimate 5.6 kg of Hg to be remobilized annually. Should permafrost disappear entirely as projected from the region until the end of the century, up to 0.7 Mg of Hg could potentially be released into the environment. Our study demonstrates that permafrost thaw is driving substantial Hg remobilization and highlights that especially vulnerable regions such as the permafrost peatlands in Scandinavia could become an important Hg source to the Arctic Hg-cycle in the coming decades.

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1 Introduction

Permafrost peatlands in boreal and sub-Arctic regions have, until recently, functioned as sinks for both carbon (C) and mercury (Hg), currently storing around 190 ±70 Pg C and 600 Gg Hg in the top 3 m of soils in the Arctic (Hugelius et al., 2014; Lim et al., 2020). These reservoirs have been exposed to increased permafrost thaw over the past decades (Biskaborn et al., 2019; Smith et al., 2022) and Arctic warming proceeds at up to four times the global average (Rantanen et al., 2022). With mean annual ground temperature close to 0°C (Christiansen et al., 2010) many permafrost peatland systems of the sub-Arctic region such as those in northern Scandinavia are considered particularly vulnerable (Nelson et al., 2001; Fronzek et al., 2006), placing them at a thermal tipping point. As thaw accelerates, both C and Hg re-enter modern biogeochemical cycles (Hugelius et al., 2020; Schaefer et al., 2020). For Hg, this means that permafrost peatlands in the Arctic could convert from acting as a long-term sink for Hg towards being an important source of Hg to surrounding ecosystems. Existing studies, however, provide conflicting evidence and our understanding of how widespread this process is, remains limited.

A key consequence of permafrost thaw, that may alter Hg cycling, is the formation of thermokarst wetlands. As permafrost peat plateaus (raised but flat peat deposits that are ice rich) or palsas (domed frozen peat with segregated ice) (Seppälä, 1986; Zoltai and Tarnocai, 1975) degrade, ground subsidence leads to the formation of thermokarst wetlands with fens and thaw ponds (Borge et al., 2017; Sannel and Kuhry, 2011). Thus previously dry soils become inundated, which, for example, can alter redox conditions, organic matter decomposition rates and potentially also Hg availability for remobilization (Thompson et al., 2025). Hg's biogeochemical cycle is tightly coupled with that of C. In peatlands, a large fraction of the soil Hg is sequestered from the atmosphere together with organic C through foliar uptake of elemental Hg (Hg^0) (Obrist et al., 2017). In

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the soil Hg accumulates through litterfall and remains strongly associated with the soil matrix, mainly the organic matter, due to Hg's strong affinity for reduced sulfur groups in organic matter (Skyllberg et al., 2000). In systems where permafrost thaw results in the remobilization of soil particles, such as for example retrogressive thaw slumps, this will also result in the export of Hg associated with these particles (St. Pierre et al. 2018). When soil containing Hg becomes inundated, Hg can also enter the dissolved pool, where it primarily is found bound to dissolved organic matter (Kolka et al., 1999; Ravichandran, 2004), and can be transported to downstream systems (Rydberg et al., 2010a). Dissolution of Hg from the soil matrix also makes it susceptible to other biogeochemical processes. Hg^{II}, for example, can be reduced by microbes and subsequently re-enter the atmosphere as Hg^0 (Costa and Liss, 1999). In addition, Hg^{II} can undergo abiotic reduction including reduction by organic matter molecules, as well as photo mediated reduction processes (Jiang et al., 2015; Li et al., 2023; Chételat et al., 2022). The conditions formed when the peat gets inundated can also favor methylation of Hg^{II}, forming monomethylmercury (MeHg). In abiotic sediments and soils, MeHg typically constitutes a small fraction of the total Hg pool (<1% up to 10-20 % in systems with high methylation rates) (Jonsson et al., 2014). In food webs, however, MeHg is biomagnified and is the main form (>95%) of Hg found in top predators (Chen et al., 2008; Dietz et al., 2022). By altering the pool of Hg available for methylation, and thus potentially the amount of MeHg available for bioaccumulation both within permafrost systems and in other locations following transport, remobilization of Hg^{II} from thawing permafrost peatlands may worsen Hg pollution (Jonsson et al., 2022).

Due to the vast amounts of Hg stored in Arctic permafrost soils (Lim et al., 2020), even the remobilization of a small fraction of this Hg could have consequences for local ecosystems and, cumulatively, the global Hg cycle. Despite these potential impacts, the stability and mobility of permafrost Hg under thawing conditions remain uncertain. Previous studies have indicated that Hg can be released from the soil matrix (Fahnestock et al., 2019; Klaminder et al., 2008; Tarbier et al., 2021) and that hydrological export of Hg can increase under thawing conditions (Rydberg et al., 2010a; Gordon et al., 2016; Zolkos et al., 2020). In a recent study, however, no evidence of altered Hg stocks was found after almost two decades of experimental permafrost thaw in a field experiment comparing experimentally thawed plots with intact permafrost peat (Haugk et al., 2026b). Further studies are needed to determine the extent of Hg loss from permafrost peatlands and the variability in these losses within and among different permafrost peatland systems. Here, we collected a total of 93 cores from five permafrost peatlands in Norway and Sweden, sampling peat plateaus and adjacent fens that represent different stages of permafrost degradation. By combining extensive within-site sampling with comparisons across multiple peatlands, we quantify Hg stocks in intact and thawed permafrost landforms, characterize spatial variabilities of Hg pools, and evaluate the potential for Hg to be remobilized during permafrost thaw in northern Scandinavia. A better understanding of Hg variability across thawing landforms is essential for determining whether permafrost peatlands will remain net Hg sinks or shift towards becoming sources under continued climate warming. This study therefore contributes to assessing the future role of thawing permafrost peatlands and its implications for the Hg cycle in a rapidly changing Arctic.

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2 Material and Methods

2.1 Samling and site description

In total, 93 cores across natural thaw gradients were collected from five Scandinavian permafrost peatlands (Figure 1): Dávvavuopmi South and North (Sweden, sampled in September of 2021) and Šuoššjávri, Karlebton and Lakselv (Norway, sampled in August of 2022). Earlier studies of these peatlands have suggested that peatland initiation occurred approximately 5000–6000 yr BP at the coastal sites Karlebotn and Lakselv and around 10 000 yr BP at the continental sites Šuoššjávri and Dávvavuopmi (Kjellman et al., 2018, Sannel et al., 2018). Permafrost aggradation began several millennia later, not until 950 cal. yr BP in Karlebotn, 600–100 cal. yr BP in Dávvavuopmi, 400-150 cal. yr BP in Lakselv and 100 cal. yr BP in Šuoššjávri (Kjellman et al., 2018; Sannel et al., 2018; Hichens-Bergström and Sannel, 2023). Surface vegetation of peat plateaus includes dwarf shrubs (e.g. *Empetrum nigrum* ssp. *hermaphroditum*, *Betula nana), Rubus chamaemorus,* lichens and mosses *(e.g. Polytrichum juniperinum, Dicranum elongatum),* whereas typical fen vegetation includes cotton grasses (*Eriophorum* spp.), sedges (*Carex* spp.) and mosses (*Sphagnum* spp.) (Kjellman et al., 2018; Sannel et al., 2018). In the field, thaw transects were visually identified when fens adjacent to peat plateaus had clear signs of recent thermoerosion (Fig. S1-S4), such as cracks in the peat surface, collapsing peat blocks, small open water bodies, difference in soil surface height and/or submerged dwarf shrubs (which usually do not grow in waterlogged conditions). Cores were taken from peat plateaus or palsas (hereon referred to as peat plateaus for simplicity), representing intact permafrost conditions (n = 47) and adjacent fens representing thermokarst conditions (n = 46). Fresh vegetation was removed prior to sampling from both landform types. For the drier peat plateau sites, the upper peat layer (up to 25 cm depth) was collected by sawing peat blocks with a knife and extracting smaller subsamples with scissors from the extracted peat blocks. Remaining active layer samples were then collected from the side of soil pits. Permafrost samples were collected in 10 cm increments by hammering a steel pipe into the ground. On the wetter fen plots, we used a Russian peat corer with a 50 cm long chamber to sample the peat. For most peat cores, peat sections were collected at 5 cm depth increments to 10 to 20 cm below the permafrost table or to the mineral layer beneath the peat. Fens were typically sampled to a depth of 50 cm, but for some fen cores deeper sections could also be retrieved. All individual samples (n=1082) were subdivided in the field, kept airtight in zip-lock bags and were transported in coolers with icepacks and then frozen as soon as possible before being transported to Stockholm University. The samples were then freeze-dried using a Heto Drywinner 6.55 freeze-drier and homogenized with either an agate mortar and/or a small electrical mill (coffee mill, DeLonghi KG40). Dry bulk density (DBD) was calculated by dividing the dry weight by the sample volume (g cm^{-3}).

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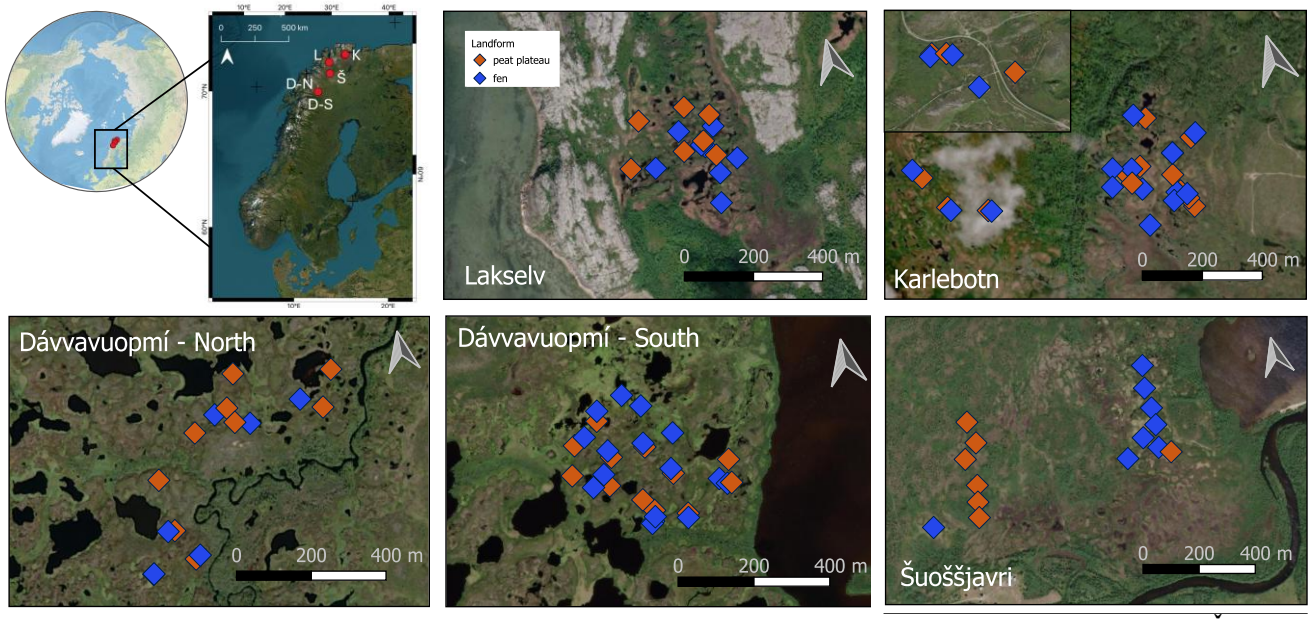


Figure 1: Sampling locations of the five study sites in northern Sweden and Norway: Dávvavuopmi South and North, Šuoššjávri, Lakselv and Karlebotn. Landform types are marked with brown circles for peat plateaus and green rhombuses for fens. All permafrost peatlands are in the sporadic permafrost zone. Map created using QGIS (version 3.44). Powered by Esri.

2.2 Chemical analysis

Hg concentration was measured using a Milestone direct mercury analyzer (DMA-80) following US EPA Method 7473 procedure. Briefly, 0.02 - 0.05 g of freeze-dried and homogenized sample was weighted into a nickel boat, which was then thermally decomposed at 900° C in the instrument to release any Hg before being preconcentrated on a gold trap and analyzed after thermal desorption in a spectrophotometer. An internal sediment reference standard (210 ± 10 ng g^{-1}) ranged between 191.2 - 224.5 ng g^{-1}, with a mean of 207.5 ng g^{-1}, standard deviation (SD) of 6.8, and relative standard deviation (RSD) of 3% (n=118). Replicate samples were chosen randomly for landform types (peat plateau, fen) and sites (Table S1).

Carbon and nitrogen (N) were analyzed using a Thermo FlashSmart Elemental Analyzer. Given the insignificant inorganic carbon content in these peat samples (mean of 0.82%, Tarbier et al., 2021), therefore all analyzed carbon is considered to be organic carbon. An amount of 2-3 mg of freeze-dried soil was packed into tin capsules. In the instrument, the samples were combusted at 950° C, products separated in a gas chromatograph and quantified with a thermal conductivity detector. By using EagerSmart software, chromatographic peaks were first automatically integrated and manually adjusted afterwards, if needed. Instrument calibration was done using 0.1 to 3 mg of 2.5-bis (5-tetra-butyl-benzoxazol-2-yl) thiophene (BBOT) at the start of every run and following every 10 samples. For quality control 0.5 mg of Methionine and 2 mg of Acetanilide were used (Table S2). Replicate samples were selected randomly for landform types (peat plateau, fen) (Table S3).

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2.3 Data treatment and analysis

Data processing and statistical analyses were performed in Python 3.12.2 (Python Software Foundation) with the pandas, NumPy, and SciPy libraries. Figures were generated using the Matplotlib and Seaborn libraries, and tables were compiled using the python-docx library.

Before statistical analysis, depth weighted core-averages and elemental stocks were calculated. Depth-weighted core-average concentrations of Hg, C and N, Hg to C ratios (R_{HgC}), C to N ratios (C/N), and dry bulk density (DBD) were calculated for the upper 30 and 50 cm of the peat profile. When measurements were unavailable for a depth interval within the targeted depth section (0-30 cm or 0-50 cm), missing intervals were filled by linear interpolation between adjacent observations or with extrapolation using the nearest measured value at the upper and lower boundaries.

Stocks of Hg (mg Hg m^{-2}) and C (kg C m^{-2}) were calculated to the observed or estimated peat depth of each core. Estimated peat depths, that were applied for cores where the mineral layer was not reached, were calculated using observed peat depth from cores where the mineral layer was reached from the same site and landform type. To avoid underestimating peat depth, cores that exceeded minimum peat depths observed in other cores from the same site and landform type were also included, with their sampled depth representing the minimum known depth constraints. For example, at Dávvavuopmi North, complete cores reached the peat-mineral interface at depths of 90-160 cm, whereas several cores reached peat to at least 240 cm depth (Fig. S5), indicating the presence of substantially deeper peat deposits than represented by the cores that reached the underlying mineral layer. For Lakselv and Šuoššjávri, we assumed the same average peat depth in fens as what was calculated in the peat plateaus, as none of the fen cores had an observed peat depth. Stocks were determined by multiplying C and Hg concentrations by DBD for each depth interval and then summing the resulting masses over the entire peat profile.

In addition to peat-depth-integrated stocks, Hg stocks were also calculated for a standardized carbon mass of 20 kg C m^{-2}. This approach was used as a control to evaluate whether differences in Hg stocks between peat plateaus and fens were influenced by differences in peat depth. First, the depth corresponding to a cumulative C stock of 20 kg C m^{-2} was determined for each core, after which Hg stocks for this depth interval were then calculated. A target C stock of 20 kg C m^{-2} was selected as it was found to correspond to the upper 40-50 cm of the peat profile in most cores and thus included the depth range where elevated Hg concentrations were observed in several cores (Fig. S6).

The normality of the data distribution was tested with the Shapiro−Wilk test and goodness of fit with Anderson-Darling test. Descriptive statistics included sample size (n), arithmetic mean, standard deviation (SD), median, first and third quartiles (Q1 and Q3), interquartile range (IQR), minimum, and maximum values. As many of the variables were right-skewed, geometric means and geometric standard deviations (GSD) were also calculated from log-transformed data. Median (Q1-Q3) and

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geometric means (GSD) was used when presenting the data in text, while arithmetic mean values were used to calculate stocks. All concentrations are reported per dry weight of soil, unless otherwise stated.

Precision-based sample size requirements were calculated as guidance for future studies of similar systems. For each variable and landform type, the standard deviation of log-transformed data was first calculated (SD_{log}). The number of samples (n) required to estimate the population geometric mean at the 95% confidence level was then calculated using SD_{log} and a specified precision factor (R). Calculations were performed for R = 1.2 and 1.5, corresponding to estimates within a factor of 1.2 (approximately ± 20%) and 1.5 (approximately ± 50%) of the true geometric mean, respectively (Equation 1).

$$n = \left(\frac{1.96 \times SD_{log}}{\ln(R)}\right)^2 \quad (1)$$

Statistical comparisons of Hg stocks between sites and landform types were evaluated using Kruskal-Wallis rank-sum test and Mann Whitney U test, respectively, using one value per core. When significant overall differences were detected ($p<0.05$), pairwise comparisons were performed using Dunn's post hoc tests with Holm correction for multiple testing using a significance level of $p<0.05$ (*), $p<0.01$ (**) and $p<0.001$ (***).

Calculations of Hg stocks, and potential loss of Hg over time, in Swedish and Norwegian permafrost peatlands sites was done assuming a combined total areal coverage of 130 km^2 (Norway: 110 km^2, Borge et al. (2017); Sweden: 20 km^2, Länsstyrelsen (2014)), and a degradation rate for peat plateaus of 0.8% yr^{-1} (Borge et al., 2017). For these estimates, we assumed, as a starting point, 100% of the area to be covered by peat plateaus that at a rate of 0.8% yr^{-1} was converted into fens.

3 Results and Discussion

3.1 Field observations and landscape heterogeneity

To investigate Hg dynamics in thawing permafrost peatlands, including variability within and among sites, we collected 93 soil cores from five permafrost peatlands within the sporadic permafrost zone in Northern Scandinavia (Fig. 1). Signs of permafrost thaw and landscape transformation were evident at all sites. At Dávvavuopmi, both gradual and abrupt permafrost thaw processes were observed, including ground subsidence and lateral erosion as well as collapsing block features and numerous actively eroding peat plateaus (Fig. S1). Similar but less pronounced conditions were observed in Karlebotn and Šuoššjávri (Fig. S2, S3), whereas Lakselv exhibited lower topographical differences between top of palsas and surrounding fens, and therefore less block erosion (Fig. S4). At peat plateaus/palsas, representing intact permafrost conditions, the permafrost table was detected within the top 1 m at 40 of the 47 sampling locations. Because the probe had a length of 1 m

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(and cores were less than 1 m deep, Table S4), permafrost may have also been present at the remaining seven locations but at greater depths. Measured average active layer thickness in peat plateaus ranged from 41 to 120 cm among all sampling locations. In the fen, representing thawed conditions, the permafrost table was not detected within the upper 1 m at any of the sampling locations, except for one fen in Dávvavuopmi South (0.5 m, Table S4). At Dávvavuopmi South, the sampled fen areas mainly consisted of small open-water bodies with visible signs of peat collapsing from the plateau into the fen, which we interpreted as evidence of recent peat collapse. At the other sites that showed signs of more gradual thaw, the fens were often vegetated. Collected cores varied in length from 30 to 240 cm, with most reaching depths between 50 and 100 cm (Fig. S5). Although we reached the mineral layer in only 37 out of the 93 cores, not including many fens, we can conclude that the peat depth varied substantially (25 cm to at least 220 cm, Table S4), with no consistent trend among sites or between plateaus and fens. High local variability in peat depth likely reflects differences in geomorphology and hydrological connectivity (Hugelius et al., 2020).

3.2 Hg variability within and between peatland sites

To better constrain changes in Hg stocks in thawing permafrost peatlands, improved insight into the variability of Hg both within and between different peatlands is needed. As expected, higher Hg concentrations were observed in the organic rich peat layer (median [Q1-Q3], geometric mean ± GSD: 42 ng Hg g^{-1} [26-79], 45 ± 2.3, n=1021), in comparison to the underlying mineral layer (5.8 ng Hg g^{-1} [3.1-9.9], 5.7 ± 2.3, n=48; $p<0.001$). Both, Hg concentrations and the ratio of mercury to carbon (R_{HgC}) were within the ranges reported from other Arctic permafrost peatlands (Olson et al., 2026 and references therein). The R_{HgC} was significantly higher in the mineral layer than in the organic layer, with median [Q1-Q3], geometric mean ± GSD, values of 0.10 ng Hg g^{-1} C^{-1} [0.070-0.18], 0.11 ± 2.0, and 0.21 ng Hg g^{-1} C^{-1} [0.070-0.70], 0.28 ± 3.5, respectively ($p<0.001$). Individual Hg observations show that fen samples are generally distributed toward the lower end of the concentration range, whereas peat plateaus had higher Hg concentrations (Fig. 2a). At all sites, elevated Hg concentrations in the top 50 cm were observed in peat plateaus (Fig. S6). Surface enrichment of Hg is consistent with earlier observed profiles of Hg at these sites we well as other permafrost peatlands (Liu et al., 2016; Tarbier et al., 2021), and has typically been attributed to increased atmospheric Hg during the industrial era (Bindler, 2003; Biester et al., 2007). As discussed in earlier work (Haugk et al., 2026a), elevated concentrations of Hg in surface peat might also be attributed to the conditions under which the different peat layers were developed and differences in peat accumulation rates, with slower accumulation following permafrost aggregation (Kjellman et al., 2018; Sannel et al., 2018; Hichens-Bergström and Sannel, 2023)).

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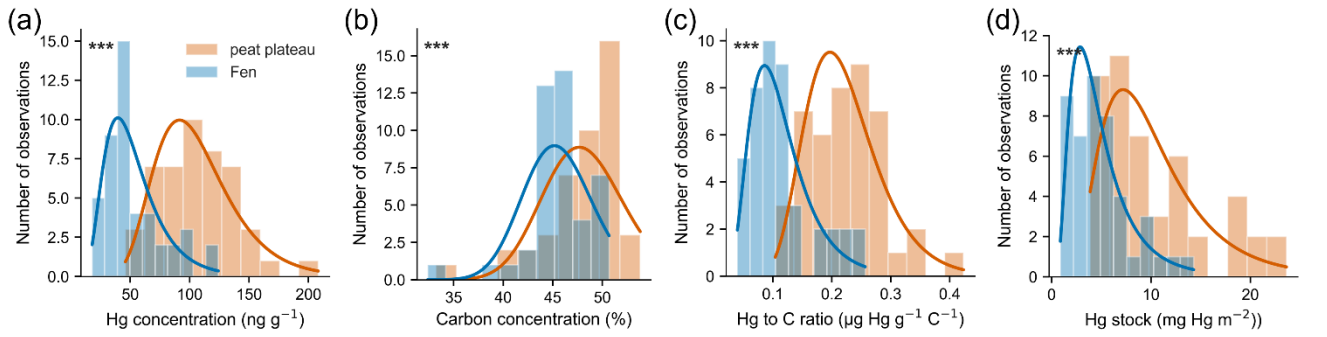


Figure 2: Distribution as per number of observations of a) mercury concentration (Hg, ng g^{-1}), b) carbon concentration (C, %) and c) ratio of mercury to carbon (R_{HgC}, µg Hg g^{-1} C^{-1}) in the upper 30 cm, and d) mercury stocks (mg Hg m^{-2}) over the peat profile. Histograms are marked by landform type (peat plateau-orange, fen-blue). Differences between landform types determined by Mann-Whitney U test with level of significance p<0.001 (***).

To explore Hg variability among collected cores as well as between peatland sites and landform types representing thaw stages, we compared depth-weighted core averages (including mineral layers if reached) of Hg and ancillary parameters (C, N, R_{HgC} DBD and C/N) for the upper 30 and 50 cm (Table 1, Table S5-S7). For Hg, higher depth-weighted core averages were observed in the peat plateaus (median [Q1–Q3]: 110 ng Hg g^{-1} [87–130] and 76 ng Hg g^{-1} [64–92] for the 0–30 and 0–50 cm intervals, respectively) than in the fens (46 ng Hg g^{-1} [38–66] and 50 ng Hg g^{-1} [37–68] for the 0–30 and 0–50 cm intervals, respectively; p-values see Table S6). Although a difference was also observed when comparing C content (p<0.001, Table 1, Fig. 2b), slightly lower C in fens cannot alone explain differences in Hg concentrations, as demonstrated by the lower R_{HgC} in fens (p<0.001, Table 1, S6, S7, Fig. 2c). Fens also had lower DBD than peat plateaus (Table S7, Fig. S7) and thus caution should be taken when comparing depth intervals between landforms as they do not necessarily represent equivalent peat mass or periods of peat accumulation. Given the observed differences between peat plateaus and fens, comparisons among the five sites were performed within each landform type. We did not observe any significant differences in Hg concentrations or R_{HgC} among the sites (Table S8).

To examine the role of peat composition for Hg concentrations and R_{HgC}, we examined patterns of C/N ratios and its relationship to Hg and R_{HgC}. The C/N ratio is widely used as a proxy for peat decomposition, but its value as a standalone indicator is limited because it can be affected by processes other than decomposition (Biester et al., 2014; Treat et al., 2016). Harris et al. (2023), for example, reported substantial C losses following the transition from peat plateaus to thermokarst bogs in western Canada, while no significant change in C/N ratios were observed. For our cores, the C/N ratio, that ranged from 21.8 to 57.2, generally decreased with depth (Fig. S6), which is consistent with greater decomposition and greater loss of C relative to N in deeper peat (Kuhry and Vitt, 1996). When comparing fens and peat plateaus, we note higher C/N ratios in fens at Karlebotn and Lakselv, while no statistical difference was determined at the remaining three sites (Table S9, Fig. S7). As

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discussed below, we observed lower stocks of C in fens in comparison to the intact peat plateaus. Our observations of lower C stocks (discussed below), combined with the absence of a systematic decrease in C/N ratios in the fens, are thus consistent with earlier observations of Harris et al. (2023) from Canadian thaw transects. We also tested the relationships between Hg and N, R_{HgC} and C/N, as well as R_{HgC} and DBD. Although some variables showed significant correlations (Fig. S8), the relationships observed within the peat were generally weak (maximum $R^2 = 0.255$) and were not consistently observed across both peat plateaus and fens. For the fens, however, the negative correlation between C/N ratio and R_{HgC}, indicates that fen peat with higher C/N contained less Hg relative to C, a trend also observed in previous studies (Obrist et al., 2011; Tarbier et al., 2021). Overall, we conclude that the additional information potentially gained from C/N ratios did not improve our ability to explain patterns in Hg concentrations or R_{HgC}.

To constrain the mass of Hg currently stored in these permafrost peatlands and assess how landscape transitions may alter this reservoir, estimates of Hg stocks are needed. Among the variables needed to calculate Hg stocks, both Hg concentration and DBD exhibited moderate higher variability (GSD = 1.3–1.5) than C concentration (GSD = 1.1–1.2). Using precision-based sample size calculations, we estimated the number of cores required to achieve a certain relative precision, assuming heterogeneity like the one observed at our sites. For Hg and R_{HgC}, 12 and 17 cores, respectively, for the peat plateaus, and 21 cores from the fens would be required for a more robust estimate with a relative precision of at least 20% (95% confidence interval). These sample size requirements are higher compared with the number of cores typically retrieved during field campaigns. If higher uncertainties are acceptable (e.g., relative precision of 50%), then 3 to 4 cores would be sufficient. However, with such a small sample size, differences between landform types such as peat plateaus and fens may be difficult to detect. This may also help explain why, in our earlier work from the same locations (Tarbier et al., 2021), we were unable to detect a statistically significant difference in Hg content between peat plateaus (n = 4) and fens (n = 5). In addition to providing valuable insight into the variability and uncertainty associated with Hg stock estimates in these environments, our high-resolution dataset highlights the importance of accounting for contrasting landform features, such as peat plateaus and fens, when estimating Hg stocks in permafrost peatlands.

Table 1: Summary statistics for peat plateau and fen. Variables include in the upper 30 cm: mercury concentration, carbon concentration, dry bulk density, C/N, Hg to C ratio (R_{HgC}); for the peat profile: Hg stock, C stock, peat depth used for calculating Hg and C stocks, peat depth (cm) corresponding to 20 kg C m^{-2}, Hg stock calculated for the upper peat with a carbon stock of 20 kg C m^{-2}. Values are reported as range, median (Q1-Q3) or geometric mean (GMD; geometric standard deviation (GSD)). P-values are from Mann-Whitney U test comparing peat plateau and fens for respective variables. Superscript n indicates the number of cores included in each peatland and landform type.

Variable	Peat Plateau			Fen			
	Range^n	Median (Q1–Q3)	GMD (GSD)	Range^n	Median (Q1–Q3)	GMD (GSD)	p-value

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[Hg] (ng g^{-1})	45.9–208.2[47]	106.6 (86.7–127.0)	101.2 (1.4)	17.9–124.1[46]	45.9 (37.6–65.9)	48.1 (1.6)	<0.001
[C] (%)	33.2–53.8[44]	49.2 (46.7–50.4)	48.0 (1.1)	32.4–50.7[43]	45.2 (44.3–47.1)	45.4 (1.1)	<0.001
DBD (g cm^{-3})	0.108–0.311[47]	0.188 (0.162–0.219)	0.184 (1.290)	0.040–0.151[43]	0.070 (0.054–0.095)	0.073 (1.446)	<0.001
C/N	15–56[44]	26 (22–35)	27 (1)	16–72[43]	40 (24–57)	36 (2)	0.008
R_{HgC} (µg Hg g^{-1} C^{-1})	0.10–0.42[44]	0.22 (0.17–0.26)	0.21 (1.34)	0.04–0.26[43]	0.10 (0.08–0.13)	0.10 (1.56)	<0.001
Hg stock (mg Hg m^{-2})	3.9–23.6[47]	8.3 (6.3–12.9)	9.1 (1.6)	0.9–14.3[45]	4.2 (3.0–6.0)	4.2 (1.9)	<0.001
C stock (kg C m^{-2})	21.9–330.1[44]	79.2 (52.1–113.7)	75.4 (1.8)	11.0–229.9[42]	37.4 (30.3–60.5)	43.1 (1.8)	0.005
Peat depth (used for integration) (cm)	25–179[47]	80 (58–105)	78 (2)	35–125[46]	102 (70–105)	93 (1)	-
Peat depth for 20 kg C m^{-2} (cm)	16–153[44]	24 (21–35)	29 (2)	30–110[42]	60 (49–77)	61 (1)	-
Hg stock (20 kg C m^{-2}) (mg Hg m^{-2})	1.6–8.9[44]	4.6 (3.5–5.3)	4.3 (1.4)	0.9–6.0[42]	2.3 (1.5–3.2)	2.2 (1.6)	<0.001

3.3 Has permafrost degradation resulted in Hg loss?

The lower Hg content in the upper 50 cm in fen profiles points toward the potential loss of Hg following permafrost thaw and peat inundation. However, determining whether permafrost degradation has led to Hg remobilization requires comparing Hg stocks to account for differences in, for example, DBD and C content (Fig. 2d, S7b, Table 1). Here, Hg stocks were calculated down to the detected start depth of the mineral layer or, when the mineral layer was not reached, estimated of local and features-specific average peat depth (Table S4). The Hg stocks ranged from 3.9 to 24 mg Hg m^{-2} and from 0.88 to 14 mg Hg m^{-2} in peat plateaus and fens, respectively, and no statistical difference was observed among the locations. When comparing Hg stocks in fens and peat plateaus, we observed two times lower Hg stocks in the fens ($p<0.001$ for full dataset as well as for four out of the five sites when testing them individually, Fig. 3), suggesting around half of the Hg originally in the peat profile has been lost due to collapse and peat inundation. The pattern of lower Hg stocks in thawed, permafrost-free features aligns with earlier observations by Klaminder et al. (2008) from two permafrost peatland ca. 80 km west of Dávvavuopmi South (Stordalen and Storflaket). In this earlier study, between the intact hummock and inundated hummock a ~40 to 95% decrease in Hg stocks was observed. Not all studies, however, report reduction in Hg stocks. In our earlier work in a long-term snow-fence experiment also at Storflaket mire, no differences in Hg stocks were observed between control (n = 6) and manipulated plots (with accelerated thaw, n = 6) after almost two decades of treatment (Haugk et al., 2026b). One possible explanation is that, despite the development of thermokarst in most manipulated plots, the timescale of Hg loss exceeds the duration of the experiment. These contrasting observations suggest that the response of Hg to permafrost thaw may depend on the stage of landscape development and we thus need a robust approach to quantify changes.

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The high spatial heterogeneity of permafrost peatlands, and particularly the large variability of peat depths (Hugelius et al., 2020), makes estimating Hg stocks in these types of ecosystems challenging. The fact that the mineral layer was not reached in a subset of the sampled cores contributes to this uncertainty (Fig. S5). To assure that the observed differences in Hg stocks between the peat plateaus and fens are not just reflecting variations in observed peat depth, we also estimated Hg stock in each core corresponding to the first 20 kg C m^{-2} (Table S10). By calculating the stocks using this second approach, we can compare the peat plateaus and fens without risking that the differences observed are driven by peat depth alone, while we still account for the difference in DBD between peat plateaus and fens (Fig. S9b, Table S7). Also here, we see lower stocks of Hg in the fens, thus supporting the first observation of substantial Hg loss as the peat gets inundated post-thaw. It should be noted that this second approach only accounts for Hg loss that results in lowering the ratio between Hg and C and does not account for the simultaneous loss of Hg and C from the system. Consequently, stocks calculated using the first approach provide a more accurate representation of the changes in the total Hg pool.

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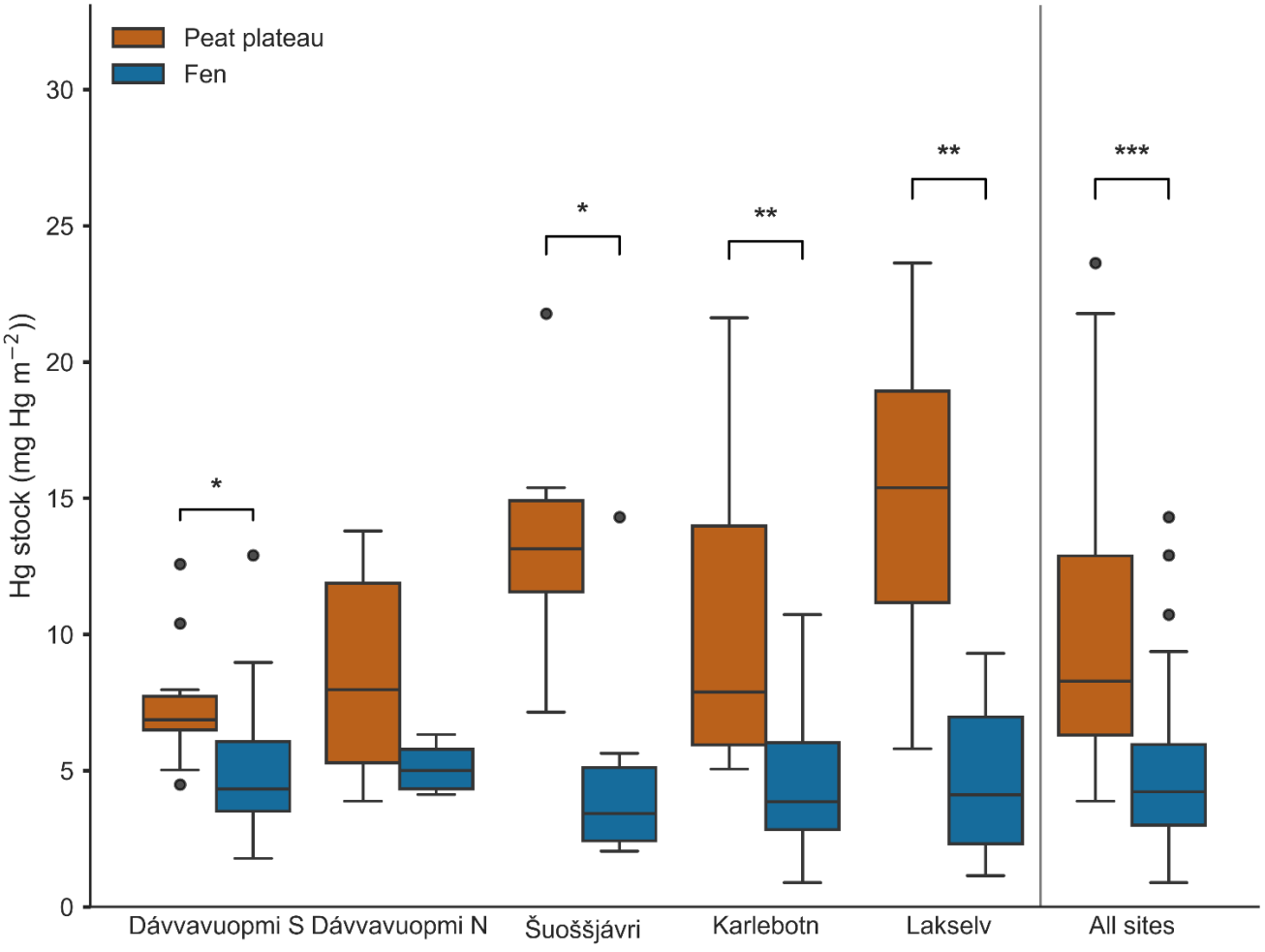


Figure 3: Mercury stocks (mg Hg m^{-2}) for sites and landform types ordered by latitude from south to north. Overall, fens (blue) have significant less Hg compared to peat plateaus (orange) with significant levels at p<0.05 (*), p<0.01 (**) and p<0.001 (***) (Dávvavuopmí South: n=23; Dávvavuopmí North: n=16: ; Šuoššjávri: n= 12; Lakselv: n=12; Karlebotn: n=30). Boxes represent the 25th and 75th percentiles, horizontal lines indicate the median, whiskers show the interquartile range and points represent outliers.

Although we demonstrate that permafrost thaw results in Hg loss, our data does not allow us to determine the fate of the released Hg. Hg loss is likely driven by a combination of physical and biogeochemical processes that occur with or are a result of active permafrost thaw. The transition from ombrotrophic peat plateau to minerotrophic fens that goes alongside permafrost degradation in peatlands (Leppiniemi et al., 2023) may alter redox conditions (Thompson et al., 2025), organic matter decomposition (Hodgkins et al., 2014) and stimulate microbial activity (Coolen et al., 2011). Enhanced microbial degradation of peat during and immediately after thaw can release previously bound Hg and changes in the water table may promote Hg reduction and evasion as Hg^0 (Li et al., 2023; Thompson et al., 2025). In addition increasing hydrological connectivity with

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further permafrost degradation, as expected for the Dávvavuopmi sites (Seemann and Sannel, 2024), may facilitate Hg transport to the wider hydrological network through mobilization of dissolved organic carbon (Fahnestock et al., 2019; Hodgkins et al., 2016). The conditions created upon thaw may also facilitate Hg methylation (Lehnherr et al., 2012; Tarbier et al., 2021). MeHg may partition more readily into porewater of wetland soils than inorganic Hg (Liem-Nguyen et al., 2017), which constitutes the majority of the Hg pool, suggesting that methylation could facilitate lateral transport of Hg downstream. However, Hg reduction or lateral transport of inorganic Hg is more likely to dominate Hg losses from collapsed peat plateaus.

3.4 Implications of future permafrost thaw for Hg stocks and cycling

Widespread loss of near-surface permafrost is projected across the Arctic over the next century and beyond (Intergovernmental Panel On Climate Change (IPCC), 2022). Due to their sporadic distribution, permafrost peatlands of northern Scandinavia are likely to disappear completely during this century (Borge et al., 2017). Current estimates suggest annual permafrost peatland degradation rates of 0.8% - 7.25% for the sites examined in this study (Borge et al., 2017; Sjöberg et al., 2015). If similar degradation rates continue, permafrost is projected to disappear from the peatlands at Lakselv and Karlebotn by 2060, from Šuoššjávri by 2080 (Gisnås et al., 2017), and from Dávvavuopmi by approximately 2230 (Sjöberg et al., 2015). The extent of permafrost peatlands in northern Scandinavia is not well constrained. Gisnås et al., (2017), presented a maximum distribution of permafrost peatlands (or palsas) in the region of 1510 km^2 (with 55% in Norway, 32% in Sweden and 13% in Finland). However, they also recognized that the actual distribution of permafrost is likely much smaller and that it's not possible to accurately project presence of permafrost in peatlands with regional models, since local factors are important for determining permafrost presence or absence. Mapping of peatlands underlain by permafrost using interpretation of aerial photographs, which probably is the most reliable method available at this time, suggests that there are around 110 and 20 km^2 of permafrost peatlands in Norway (Borge et al., 2017) and Sweden (Länsstyrelsen, 2014) respectively. Assuming a total area of 130 km^2, we estimate permafrost peatlands in Sweden and Norway to currently store 1.3 Mg of Hg (ranging from 0.5 to 3.0 Mg Hg). Using a degradation rate for peat plateaus of 0.8% yr^{-1} (Borge et al., 2017), we further estimate the annual rate of remobilized Hg to be 5.6 kg Hg yr^{-1} (ranging from 3.2 to 9.7 kg Hg yr^{-1}). This corresponds to a cumulative Hg remobilization of 49 kg Hg over the next decade, if the rate of degradation remains constant in the future. Although these estimates do not account for the temporal delay between peat collapse and Hg remobilization, they likely provide a reasonable representation for continued net Hg release as permafrost thaw is an ongoing long-term process. Should all existing peat plateaus transition into fens, up to 0.7 Mg Hg could ultimately be remobilized from the Swedish and Norwegian permafrost peatlands upon complete permafrost degradation. This is a significant amount of Hg, considering that the Arctic atmosphere and upper ocean (0–500 m) are estimated to contain approximately 330 and 500 Mg Hg respectively (Dastoor et al., 2022), and that our estimate accounts for losses from only a small fraction (around 0.2 %) of the Hg stored in northern permafrost soils (approximately 600 Gg Hg in the upper 3 m of Arctic permafrost soils, Lim et al., 2020). Although the permafrost peatlands included in this study may not represent all Arctic permafrost peatlands, the vast size of the remaining permafrost Hg reservoir, much of which is located in

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regions projected to thaw over longer timescales, highlights the potential for substantially greater Hg remobilization from Arctic peatlands as permafrost degradation continues.

Predicting future mobilization of Hg from thawing permafrost systems is complex because of the unpredictable nature of landscape transitions over time. In addition to ground subsidence, peat inundation and altered vegetation cover, permafrost degradation can in the long run also alter hydrological pathways, and result in the drainage of inundated peat (Liljedahl et al., 2016; Olefeldt et al., 2021). These processes would thus likely alter the capacity of the landscape to capture Hg from the air (Rydberg et al., 2010b). However, given the long timescales (centuries to millennia) over which the Hg currently stored in Arctic permafrost had accumulated, these landscapes are likely to remain a substantial net source of Hg for the foreseeable future. In our previous study of Hg accumulation under different vegetation regimes in permafrost peatlands, net accumulation rates ranged from 0.3 to 2.6 μg Hg m^{-2} yr^{-1} (Haugk et al., 2026a). Even if the highest observed rate were sustained, it would take approximately 2,000 years for all peatland area currently predicted to be underlain by permafrost in Sweden and Norway to re-accumulate the 0.7 Mg of Hg potentially released upon complete thaw.

The extent to which remobilized Hg alters exposure risks for humans and wildlife depends on the environmental fate of the released Hg. Based on our observations, we cannot determine whether the mobilized Hg was primarily removed through reduction followed by evasion to the atmosphere, or whether it was exported to downstream aquatic systems. Previous work, where the atmospheric flux of Hg was quantified along similar thaw gradients, does not support increased evasion upon thaw (Fahnestock et al., 2019). It should, however, be noted that seasonal data is currently missing, and that such data potentially could support evasion as the main mechanism of Hg removal. In another study, by St. Pierre et al. (2018), substantial Hg transport from retrogressive thaw slumps was demonstrated through the mobilization and downstream transport of particulate material. Given that our thermokarst fens had rather still standing water, we argue that the Hg is more likely to be remobilized and transported in the dissolved phase, while bound to dissolved organic matter, or lost to the atmosphere, than attached to particles. If at least a part of the released Hg is transported downstream into local coastal systems, it could potentially contribute to an already existing contamination in sediments and biota (Dietz et al., 2022), enhancing bioaccumulation in fish (Amptmeijer et al., 2025) and ultimately increasing the exposure risk for humans. If released to the atmosphere, remobilized Hg could contribute to regional or global Hg cycling and potentially counteract, at least in part, ongoing efforts to reduce anthropogenic Hg emissions under the Minamata Convention (Minamata Convention on Mercury, 2024). Future efforts should focus on understanding the fate of remobilized Hg to constrain the future role of permafrost peatlands in the Arctic Hg cycle.

4 Conclusion

Here, we demonstrate significant loss of Hg from thawing permafrost peatlands across five different sites located in northern Scandinavia. These observations are in line with observations done in some (Klaminder et al., 2008) but not all previous studies

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(Haugk et al., 2026b). A key strength of the current study is the large number of peat cores and within-core Hg measurements collected, which allowed us not only to explore variabilities in Hg and related parameters among and within sites, but also to provide a robust foundation for our conclusion that Hg is lost following permafrost thaw. With northern Scandinavian peatlands undergoing widespread permafrost degradation and landscape changes, they offer an important indication of how Hg cycling may respond to continued warming elsewhere across the Arctic. Although the long-term fate of Hg in these environments remains uncertain due to complex thaw trajectories, a better understanding of Hg transformation processes and the potential re-accumulation of remobilized Hg is needed. Continued monitoring and investigation of Hg dynamics will be essential for predicting future Hg cycling and assessing the contribution of climate-driven Hg release to the global Hg budget.

Data availability

https://doi.org/10.17043/haugk-2026-7mhh80-1

Supplement link

The link to the supplement will be included by Copernicus, if applicable.

Author contributions

CH and SJ conceptualized the work. CH planned and CH, AA, BS, JW and SJ carried out fieldwork. CH conducted laboratory work and data analysis. Manuscript writing was led by CH with major contributions of SJ. All authors contributed to the manuscript and have given approval of the final version.

Competing interests

The authors declare no competing financial interest.

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Review statement

The review statement will be added by Copernicus Publications listing the handling editor as well as all contributing referees according to their status anonymous or identified.

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