

Pb and Fe flow through the mire-lake complex of Skogaryd catchment - a system under anthropogenic influence

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20 **Abstract**

Sphagnum dominated peatlands store not only vast amounts of carbon (C) but also metals derived from bedrock and anthropogenic sources. Some metals are involved in peat C stability, and some are toxic to living organisms. However, the pools of such metals and their export in relation to export of C in the form of dissolved organic C (DOC) in mire-lake complexes have received little attention. We characterized a hemiboreal mire in Sweden previously exposed to heavy metal pollution in terms of physiochemistry, age, total C pool, lead (Pb) and iron (Fe) content. We investigated export of Fe and Pb in relation to DOC in the mire-lake complex. We found strong and linear correlations of Fe and DOC export in streams and the export occurred in similar ratios from both the ~~lake and mire and the downstream lake~~. The export of Fe and DOC seemed to be controlled by hydrological connectivity, while the production of DOC and ~~mobilisation of Fe and Pb~~ most likely was ~~controlled by highest at low water drought conditions table depth leading to oxic conditions~~. We found the Pb content exceeded threshold values for toxicity in the top layer of the peat and in stream water leaving the mire. Stream water concentrations of Pb were as for Fe and DOC, highest after drought periods. ~~Pb-Lead~~ isotope analysis revealed that Pb leaving the mire accumulated through anthropogenic contamination (most likely ~~from~~ gasoline), while Pb leaving the lake ~~seemed to also contain natural sources, but with an additional from the geological background. In addition~~
35 ~~addition~~, the lake appeared to be a sink for the anthropogenic Pb ~~leaving-exported from~~ the mire through sedimentation. This study suggests that peat decomposition in peatlands affected by climate change may pose a risk to not only losing stored C, but also through release of heavy metals to the local environment.

40 1 Introduction

Peatlands hold vast amounts of organic carbon (C), equivalent to 20-30% of the global pool of soil C (Gorham, 1991). Peat is formed over thousands of years and is preserved in the deep peat layers under waterlogged and anoxic conditions (Wilson et al., 2016). Large pools of metals from both atmospheric deposition and parent bedrock are bound in peat. Some metals like iron (Fe) are involved in peat stabilisation and degradation (Qin et al., 2022; Wang et al., 2017) and some metals like lead (Pb) are toxic to living organisms (Rothwell et al., 2005; Tipping et al., 2003). Climate changes are expected to cause longer periods of drought in the boreal zone (Helbig et al., 2020) with a concurrent decrease in precipitation during summer and [an](#) increase during winter (Dore, 2005; IPCC, 2021). As a result, peatlands in the boreal zone will experience periodically lower water table, particularly in summers, and more extreme rain events (Zhong et al., 2020). These changes to peatland hydrology might expose the deeper peat to oxygen and promote C turnover (Chen et al., 2020; Fenner & Freeman, 2011; Zhang et al., 2025). [This will lead to loss of C from peatlands on different forms like CO₂ from microbial respiration, but also in the form of dissolved organic carbon \(DOC\) that is lost through water streams](#) (Prijac et al., 2023). This loss of DOC can stimulate metal export from peatlands [ecosystems, DOC from peatlands have as metals tend to be co-exported with DOC](#) (Aleshina et al., 2024; Broder & Biester, 2017) [higher affinity for binding metals.](#) [Changes in peatland hydrology and climate is known to affect export of DOC and metals from peatlands \(Broder & Biester, 2017; Prijac et al., 2023; Zhong et al., 2020\), but whether the concentrations of heavy metals reach concentrations that requires attention in relation to ecosystem function both in peatlands and downstream catchments is not well understood.](#) [How the export of DOC and hydrology affect the transport of metals is unknown for most peatlands.](#)

60 ——— *Sphagnum* mosses dominate the vegetation in boreal peatlands and are here the main contributors to peat formation. Acidic and phenolic compounds in the *Sphagnum* cell wall provide a high cation exchange capacity (CEC) and *Sphagnum* and *Sphagnum* derived peat efficiently binds positively charged ions such as metals (Clymo, 1963; Verhoeven & Liefveld, 1997; Zhao et al., 2023). As such, peatlands are efficient sinks for natural and anthropogenic derived metals (Roux et al., 2004; Shotyk et al., 1996). In addition to the recalcitrant litter of *Sphagnum*, the environmental conditions of peatlands such as cold temperatures and waterlogged conditions contribute to peat accumulation and thus metal sequestration (Aerts et al., 1992; Moore & Basiliko, 2006; Thomsen et al., 2025). Distribution of metals in the [vertical peat depth](#) profile from the living top layer to the deep peat depends on the source of the metal. Iron is one of the most abundant metals in peatlands and [is](#) mainly derived

from bedrock, with a relatively small contribution from wind-blown dust (Osborne et al., 2024; Steinnes et al., 2005). Therefore, Fe concentrations typically increase with peat depth.

~~Toxic heavy metals such as Pb, are anthropogenically sourced through deposition and are generally found in the top peat layers (Novak et al., 2011). Peatlands sequester a larger proportion of heavy metals than other ecosystems (McCarter et al., 2024), but to which extent metals bound in peat are mobilised and affect downstream ecosystems are not that well understood.~~

During the last decade, Fe has been increasingly investigated because of two proposed mechanisms influencing peat stability. Firstly, the “iron gate” theory suggests that oxidation of Fe, which occurs during water table decline, induces complexation between Fe and lignin-like compounds (Wang et al., 2017). This complexation seemingly leads to resistance against mineralization (Riedel et al., 2013; Wang et al., 2017). However, the degree to which Fe-bound peat is protected is not entirely clear and the protecting effect of Fe may be limited to static oxic conditions (Chen et al., 2020). At the same time, oxic conditions can also promote production of DOC and release of CO₂ from OM through abiotic reactions in addition to microbial breakdown and mineralization (Brouns et al., 2014; Fenner & Freeman, 2011; Qin et al., 2022; Strack et al., 2008). Specifically, abiotic Fe-mediated reactions occur in the presence of oxygen and DOC (Miles & Brezonik, 1981) and have been shown to be relevant in peat (Thomsen et al., 2025) and industrial biorefineries (Peciulyte et al., 2018) leading to a substantial contribution ~~of~~ CO₂ production through decarboxylation processes (Page et al., 2014; Trusiak et al., 2018). These reactions depends on Fe’s ability to redox cycle (Koppenol & Hider, 2019) and primarily occur at the oxic-anoxic interface around the water table (Qin et al., 2022; Wang et al., 2022; Yu & Kuzyakov, 2021). Therefore, changing water table level ~~can~~ influence DOC concentrations and CO₂ release from peat. In that regard, it is also important to mention that changes in redox conditions affect the solubility of Fe and DOC even without degradation taking place (Knorr, 2013). Understanding how fluctuating exposure to oxygen will affect DOC and Fe export from peatlands should therefore be considered in relation to future climate changes when assessing mire C dynamics.

Toxic heavy metals such as Pb, are anthropogenically sourced through deposition and are generally found in the top peat layers (Novak et al., 2011). Lead has been one of the most prominent heavy metals in a variety of industries (Tchounwou et al., 2012) and Pb pollution can be traced in different depositional environments such as lake and offshore sediments as well as peat and peatland vegetation (Bindler et al., 1999; Bränvall et al., 2001; Kylander et al., 2013; Renberg et al., 2000) ~~(Bindler et al., 1999; Kylander et al., 2013).~~ In addition, peatlands sequester a larger proportion of heavy metals compared to other ecosystems (McCarter et al.,

100 [2024](#)). The primary recent source of Pb in mires is from anthropogenic pollution as car fuel and ship paint that increased at the start of the industrial revolution and peaked in the 1970s (Marcantonio et al., 2000; Renberg et al., 2000). The isotopic composition of Pb can be used to fingerprint the source (anthropogenic versus natural) of Pb and even differentiate between types of contamination (Gmochowska et al., 2019; Jeong et al., 2023). [Lead](#) is toxic to microorganisms, plants and humans and accumulates in the ecosystem (Collin et al., 2022). [Identifying the source of Pb can indicate whether the problem is from persistent contamination from human activities and could pose an ecological risk.](#)

105 ~~The maximum allowable concentration in waters for Pb as set by the European Union (EU directive, 2013) is 14 $\mu\text{g L}^{-1}$, in sediments 163 mg kg^{-1} dry weight and in biota 110 $\mu\text{g kg}^{-1}$ wet weight (Sjöberg, 2016). The high cation exchange capacity CEC of *Sphagnum* results in strongly bound Pb, which suggests efficient safekeeping of Pb in mires under stable conditions (Dinake et al., 2019).~~

110 Due to the toxic nature of Pb, its ~~mobility transport~~ is important to understand, particularly in potentially Pb polluted peatlands [from which Pb can be mobilised and exported to downstream catchments](#) (Choudhury & Panda, 2005; Doelman & Haanstra, 1979; Shakya et al., 2008). [A large proportion of pollution derived Pb deposited in Swedish peatlands will eventually end up in downstream ecosystems such as lake sediments](#) (Brännvall et al., 2001), where it will accumulate and potentially reach harmful concentrations for benthic living organisms.

115 [Several key processes exhibit control on metal export from peatlands, such as pH and the different metal's binding affinity to DOC, but hydrological connectivity and seasonality, which includes drought and precipitation events, seems to be most important](#) (Broder & Biester, 2015, 2017; Prijac et al., 2023). [In bogs, DOC is primarily produced from decomposition, which is likely the main mobilisation process of Fe and Pb](#) (Broder & Biester, 2017). Temperature is important for DOC production as it affects decomposition rates (Rosset et al., 2022), but [the most important factor is likely oxygen availability that is linked to water table depth and enables degradation of accumulated lignin-like compounds in the peat](#) (Fenner & Freeman, 2011; Freeman et al., 2001). [Water table decline primarily occurs during warm and dry periods during summer and early fall. Typically, at this time of year the highest export and stream water concentrations of DOC, Fe and Pb is observed and particularly in relation to high discharge events where hydrological connectivity between peatland and stream re-establishes](#) (Broder & Biester, 2015, 2017; Clark et al., 2007; Prijac et al., 2023). ~~PbLead~~ is very immobile in peat and is therefore [primarily found bound in the top parts of peat](#) ~~High concentrations of Pb at the top of the mire, indicate that Pb is hardly transported vertically~~ (Kharanzhevskaya et al., 2023; Mariussen et al., 2017; Okkenhaug et al., 2018), [while redox active metals as Fe will change mobility depending on redox conditions as occur from water table fluctuations](#) (Knorr, 2013; Strack et al., 2008). [Nevertheless, both metals have a high binding affinity for OM and](#)

is commonly found to correlate with DOC in water streams leaving peatlands, a relationship that is partly explained by the high binding affinity (Aleshina et al., 2024; Neubauer et al., 2013; Okkenhaug et al., 2018; Vile et al., 1999). Dissolved organic carbon from peatlands might even have a higher binding affinity to metals due to high contents of polyphenolic compounds, seemingly derived from *Sphagnum*, compared to DOC supplied from other types of catchments (Kaal et al., 2017). The strong correlation between Pb and DOC is likely important for the total export of Pb from peatlands, but it could also have implications for the retention of Pb in downstream systems. Therefore, the expected increase in drought periods and extreme precipitation events in light of climate change, (Broder & Biester, 2017) might lead to higher exports of DOC, Fe and Pb from peatlands (Broder & Biester, 2015; IPCC, 2021; Zhong et al., 2020).

~~even under dry conditions and heavy precipitation events. However, Pb in stream water from ombrotrophic peatlands has been shown to positively correlate with DOC, suggesting horizontal export of Pb could be related to peat degradation.~~ In this study, the overall aim of this study was to investigate the relationship between export and stream water concentrations of DOC, Fe and Pb in a mire-lake complex and assess if Fe and Pb occurred in concentrations high enough to have potential effects on ecosystem functioning. In addition, we characterized the mire in terms of physiochemistry, age and total C content. The studied mire-lake complex is located inland from the west coast of Sweden and is subjected to recent climate change and exposed to heavy metal pollution. The mire-lake complex is part of Swedish research infrastructure for ecosystem research that provides continuous data on soil, air and water status. Based on previous findings (Aleshina et al., 2024; Broder & Biester, 2015, 2017), we expected to find strong correlations between Fe, Pb and DOC in stream water from the mire. In addition, we expected the concentrations would be highest following drought periods when hydrological connectivity between mire and stream would re-establish (Broder & Biester, 2015, 2017). Also, specifically for the investigated mire-lake complex, we wanted to investigate if Pb would surmount to any concentration of ecological risk in relation to EU guidelines for freshwater threshold values and in that regard determine the source of Pb pollution. In relation to Fe, we wanted to assess if the proposed mechanism of peat stability and peat destabilisation could be relevant in the studied mire-lake complex. In comparison to most previous studies, this study presents a 4-year period of export and concentration data including one year with unusual drought (2018). This long-term dataset can help identify patterns and give a more stable view of export trends in the studied system and the mechanisms behind. (Aleshina et al., 2024; Neubauer et al., 2013; Smieja Król et al., 2022; Vile et al., 1999)(Kaal et al., 2017). Whether anthropogenically sourced Pb reaches toxic

levels in peatlands and if the export of such Pb increases with concurrently higher export of DOC over time is largely unknown for most peatlands.

(Broder & Biester, 2017; Prijac et al., 2023)(Aleshina et al., 2024; Broder & Biester, 2017; Neubauer et al., 2013)

When peat is degraded via microbial decomposition, DOC is produced. In peatlands, temperature is important for DOC production (Rosset et al., 2022), but the most important factor is likely oxygen availability that is linked to water table depth (Fenner & Freeman, 2011; Knorr, 2013; Strack et al., 2008).

The controls on metal export from peatlands are not well understood, but export is influenced by pH, the binding affinity of peat, hydrological conditions and commonly, the export of metals from peatlands correlate with DOC (Curtinrich et al., 2024; McCarter et al., 2024). ~~When peat is degraded via microbial decomposition, DOC is produced. In peatlands, temperature is important for DOC production (Rosset et al., 2022), but the most important factor is likely oxygen availability that is linked to water table depth (Fenner & Freeman, 2011; Knorr, 2013; Strack et al., 2008).~~ Meanwhile, the transport of DOC is primarily affected by runoff and precipitation (Clark et al., 2007; Koehler et al., 2009). Consequently, DOC concentrations are highest in the upper parts of peat and above the water table (Clark et al., 2008; Strack et al., 2008). Export of metals, and in particular metals with high binding affinity to DOC, such as Fe and toxic heavy metals, increases during and after drought. Extreme precipitation events could therefore mobilise the pools of metals accumulated after increased oxygen availability following retracting water table in peatlands.

(Broder & Biester, 2017)(Prijac et al., 2023)Here, we investigated a mire lake complex inland from the west coast of Sweden subjected to recent climate change and exposed to heavy metal pollution. The mire lake complex is part of Swedish research infrastructure for ecosystem research that provides continuous data on soil, air and water status. We wanted to characterize the mire in terms of physiochemistry, age and total C content and evaluate the pools and export of Fe and Pb in relation to DOC in the light of future climate

2. Materials and methods

190 2.1 Site description

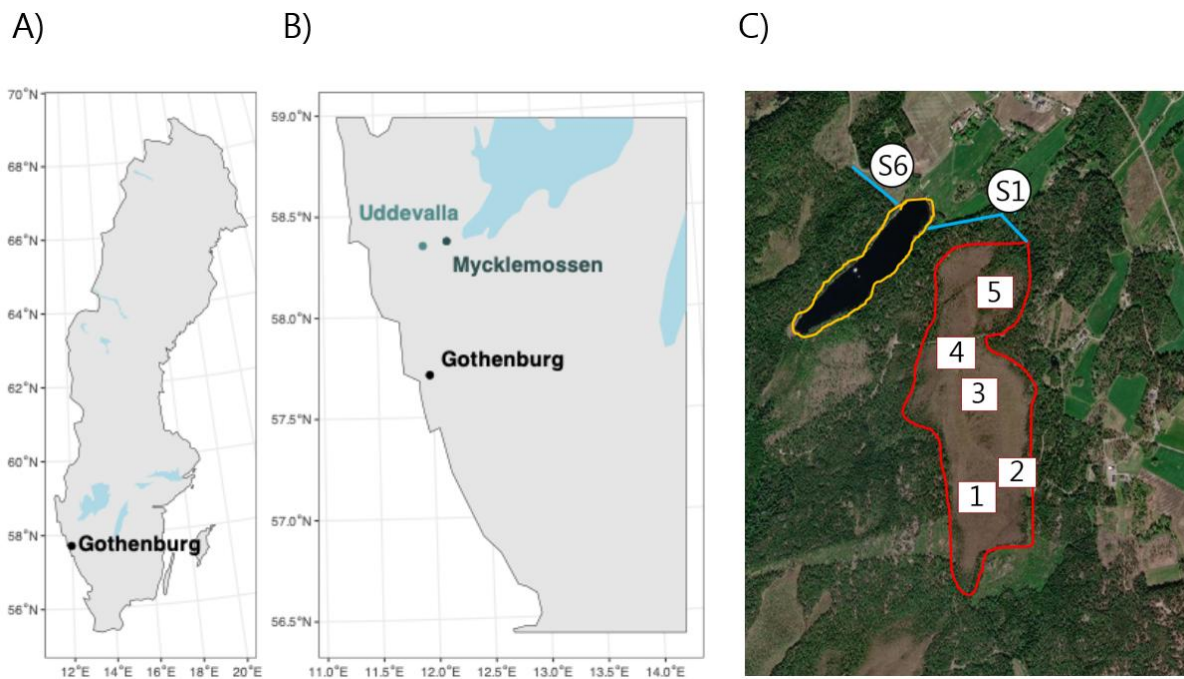
This study was conducted for the period 2017-2021 in Mycklemossen mire and Ersjön lake (58°21' N, 12°10' E; 80 m a.s.l.), which are part of the Skogaryd research catchment in the hemiboreal forest zone in southwestern Sweden. The Skogaryd research catchment is part of the Swedish Infrastructure for Ecosystem Science (SITES). Air temperatures range between -0.8 °C in February and 16.8 °C in July and precipitation is highest in July to
195 December with approximately 75 mm per month and driest January to March with approximately 54 mm per month (Swedish Meteorological and Hydrological Institute normal means for the period 1991-2020, Fig. S1). During the survey period, the highest annual precipitation was in 2019 and 2020 with 1150 and 1100 mm annually, respectively. The lowest annual precipitation was 580 mm in 2017 (<https://www.fieldsites.se/SITES>). Due to climate change, summers (June, July and August) at the west coast of Sweden are predicted to receive 7% less
200 rain in June - August, 13-18% more rain in December to February and annually be 2.2 – 3.1 °C warmer by 2041-2060 in reference to preindustrial levels (IPCC, 2021).

Mycklemossen mire is a nutrient poor fen [with a surface topography composed of a mosaic of hummocks and hollows, referring to parts of the vegetation found above and below the water table respectively, and transition zones called intermediate in our study with hummocks as the dominating topography](#) (Rinne et al., 2022). [The hummocks are mainly dominated by *Eriophorum vaginatum*, *Calluna vulgaris* and *Erica tetralix* and the hollows consists of different *Sphagnum* species, mainly *S. rubellum*, *S. fallax* and *S. austinii* as well as *Rhynchospora alba*, and the peat samples were sampled approximately within a square meter plots](#) (Kelly et al., 2021). ~~with bog characteristics in its vegetation such as *Sphagnum* species as the peat forming plants.~~ Two streams lead away
205 from Mycklemossen. One runs from the north into the lake Ersjön (this stream is hereafter referred to as S61) and the other runs into a neighbouring catchment. Ersjön is 0.061 km², 4.5 m deep in the deepest part and has characteristics of a mesotrophic lake. Ersjön is sourced from Mycklemossen and from a neighbouring mostly forested catchment and drains through a stream (hereafter referred to as S6). The total catchment area of Mycklemossen (S1) is 0.595 km² and the catchment of Ersjön (S6) is 1.337 km². ~~(Table S1). The sizes of the~~
210 ~~catchments have been generated based on detailed topographic maps in relation to the location of the measuring stations (out-flow).~~ The [Skogaryd Research Catchment](#) is [located](#) in one of the densest populated areas in Sweden and east of a highway and a former industrial ship wharf. In Europe, gasoline contained Pb from 1922 until it was

220 banned in 1998. Mycklemossen is downwind from a potential source of industrial pollution, Uddevalla ship wharf. The ship wharf actively produced ships in the years of 1946 to 1985 and used Pb containing antifouling paint. The area can therefore be expected to have been subjected to considerable Pb pollution during a period of 70 years.

2.2 Peat sampling

225 On March 3rd, 2021, one peat core of 4.5 m depth was sampled at five locations in three topography types: hummock, intermediate and hollow with 1-2 meters apart. This resulted in 15 peat cores in total. The five locations were chosen to represent Mycklemossen (Fig. 1). The top 50 cm of the peat was sampled with a hand saw. The deeper peat was collected with a stainless-steel, cylinder-shaped Russian peat corer (inner dimensions: 5 cm in diameter). Just after sampling, the peat cores were sliced into 5 cm segments and frozen.



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Figure 1. A) Map of Sweden, B) Mycklemossen mire located east of Uddevalla where a ship wharf was active until 1985, C) the mire-lake complex comprising of Mycklemossen mire (encircled in red) and lake Ersjön (encircled in yellow). Sampling points in Mycklemossen are marked as 1-5 and the stream sampling location from Mycklemossen are marked as S1 and the stream from Ersjön—stream as S6. Satellite photo from <https://meta.fieldsites.se/resources/stations/Skogaryd>.

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2.3 Radiocarbon dating of peat

Peat age was determined by radiocarbon dating in samples from 20-25 cm, 120-125 cm and 420-425 cm depth from hummock, intermediate and hollow from sampling location 3 (Fig. 1C). Samples were freeze dried and
240 homogenized prior to analysis for ^{14}C at the Tandem laboratory (Uppsala, Sweden), using a MICADAS accurate accelerator mass spectrometry, following routine sample preparation by the tandem laboratory (Salehpour et al., 2013).

2.4 Physical and chemical characterization of peat

245 For all 15 peat cores (locations 1-5, Fig 1C) the top 5 cm of each 100 cm increment from 0-5 cm below surface to 400 cm (0-5 cm, 100-105 cm, 200-205 cm, 300-305 cm and 400-405 cm) were analysed for physical and chemical properties. pH was analysed in filtered peat pore water (Metrodam 691 pH Meter; Swiss). Subsamples of peat was oven dried at 40 °C until constant mass. Dry matter (DM) content was used to determine peat bulk density. Soil organic matter content (SOM) was determined from loss on ignition at 550 °C for 8 hours in a muffle
250 furnace (Heraeus Instruments). For total C, total N, $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$, dried samples were ground and weighed (5 mg) into tin capsules and analysed with a GSL elemental analyzer coupled to an isotope ratio mass spectrometer (IRMS, Sercon 20-22, Sercon Ltd., UK).

2.5 Total pools of C and N in mire

255 To map the three-dimensional layout of the mire, bathymetry, which is based on ground penetrating radar was performed. The radar measurements were carried out with Malå Geoscience Ramac ground penetrating radar with a shielded 250 MHz antenna. Measurements were collected at a sampling frequency of 2600 MHz and radar depth scans were made every 0.1 m in the different transects. For the radar measurements, the mire was divided with 4 lines from south to the north, and 10 lines east to west, forming a grid of 27 intersections, which were surveyed.
260 The radar measurements were calibrated against 5 soil cores taken in grid intersections using a “Russian corer”. Bathymetry data was illustrated with QGIS 3.18 and the data is available on the SITES data portal (https://hdl.handle.net/11676.1/lmj-WqsZXOi5T_XafhHU75Ps). The bathymetry data were combined with peat bulk density and C and N content to calculate total C and in increments of 50 cm depth. Specifically, total soil volume layer (m^3) at each 50 cm increment was multiplied by depth-specific peat bulk density (g m^{-3}) and the average fraction of C or N.

2.6 Heavy metals in peat cores

The concentration of some of the highest ranked heavy metals to consider for public health (Pb, Hg, As and Cd) (Tchounwou et al., 2012) and Fe were quantified in technical triplicates of the peat samples at 10-15cm, 15-20cm, 20-25cm, 120-125cm and 420-425 cm depth with inductively coupled plasma-mass spectrometry (ICP-MS) (iCAP, ThermoScientific) (SI Table S42). Prior to analysis, peat samples were freeze-dried and homogenized with a mortar and pestle. A subsample of 0.3 g was weighed into a Teflon bomb and 10 mL of concentrated nitric acid (70 %) was added. The samples were heated in a microwave with a ramping phase of 20 minutes and a hold phase of 25 minutes at 180 °C. After cooling, the solutions were first diluted to 50 mL with MilliQ water and further diluted 10-fold before analysis.

2.7 Concentrations and export of DOC and metals in stream water

Manual grab samples from the streams were taken fortnightly during the ice-free period for chemical analysis. Water samples were filtered through 0.7 µm pore size prior to analysis. DOC was measured via spectrometry Shimadzu TOC-VCPH. Lead (~~Pb~~) and iron (~~Fe~~) concentrations were analysed using an Agilent 8800 Triple Quadrupole ICP-MS at the Microgeochemistry Laboratory, University of Gothenburg. Samples, reference waters, and blanks were prepared in 2% HNO₃ with internal standards (Re, Rh, Ge) added for drift and matrix correction. The ICP-MS operated in MS/MS mode with NO₂ as the reaction gas. Each analyte was analyzed in four replicates of 25 sweeps at three points per peak (0.02 a.m.u. spacing). Pb was measured on mass (²⁰⁶Pb) and Fe as oxide (^{56→72}Fe), with dwell times of 0.5 s for and 0.3 s respectively. Quantification was done in the MassHunter Workstation Software v4.4. using a six-point calibration curve (0–1000 µg/L) from the Periodic Table Mix 1 (TraceCERT®, Sigma Aldrich).

Discharge calculations ~~were~~ based on continuous stream level measurements using an ISCO 2110 ultrasonic flow module (Mire north) and Mjk 1400 0-1m (Ersjön outlet, S6), respectively. Location-specific stream level discharge relation curves have been established. The data were gap-filled when necessary either via linear interpolation for shorter gaps, or by cross-correlations with nearby measurement locations within the Skogaryd catchment for longer gaps. Longer gaps usually occurred during low-flow conditions. The export of DOC and metals was calculated for each manual water sampling as the product of discharge and concentration. Linear interpolations between sampling dates were done to estimate annual export rates.

2.8 Pb isotope ratios in stream water

To determine the source of Pb in the mire catchment the composition of Pb isotopes was determined in stream water from both the mire and lake from the manual grab samples collected between February 2022 and May 2024 (N=25) for the mire, and between May 2022 and May 2024 (N=21) for the lake, respectively. The Pb isotopic composition was analysed in the Microgeochemical Laboratory at the University of Gothenborg using an Agilent 8800 ICP-MS/MS coupled to an ASX-500 autosampler, a peristaltic pump, a concentric glass nebulizer (MicroMist) and a Scott double-pass quartz glass spray chamber. The autosampler was placed in an ISO 5 clean room and was connected to the ICP-MS in the adjacent laboratory with an approximately 1 m long tubing. All sample preparations were performed in the ISO 5 clean room using Milli-Q water and ultrapure nitric acid (NORMATOM®, VWR chemicals). The ICP-MS was run in MS/MS mode with N₂O as reaction gas. A comprehensive description of Pb isotopic analysis is given in the supplementary information together with summary of ICP-MS/MS settings, acquisition parameters and reference materials used (Table S23, S43, S45). Uncertainties of the Pb isotopic composition are reported at 2s and include quadratic addition of the standard error for the 10 replicates, the excess scatter of the primary reference solution NIST SRM 981 for the respective ratio from the measurement session and the uncertainty in the ²⁰⁴Hg correction. The uncertainties from the published ratios for the primary reference material (approximately 0.04%; NIST SRM 981, (Cantanzaro et al., 1968) would need to be propagated to add systematic uncertainties. These uncertainties are considerably smaller than the random uncertainties (approximately 0.30%) and thus do not significantly contribute to the total uncertainties when added in quadrature.

To determine the fate of anthropogenic Pb in the mire-lake complex, we applied an isotope mixing model (Eq. 1). Assuming ~~that~~ Ersjön receives Pb from two different sources, water from Mycklemossen and other sources from the surrounding forest with distinct isotopic value. ~~Hence,~~ the mixing model used is:

Equation 1.
$$R_{Ersjön} = f_1 \times R_{Mycklemossen} + f_2 \times R_{forest}$$

With R being the isotope ratio of Pb and f being the relative contribution of the two sources, ~~with f₁ + f₂ equal to 1.~~ The model was applied both with the ²⁰⁶Pb/²⁰⁷Pb and ²⁰⁸Pb/²⁰⁶Pb ratios, using the IsoError tool (Phillips & Gregg, 2001) that provides mean contributions in addition to an uncertainty estimate. ~~11~~ samples from a forest stream within the Skogaryd catchment were analysed in 2023.

2.9 Data handling and statistics

Data were analysed and visualized in R version 4.3.3 (R Core Team, 2024). For parameters measured in peat, we tested the effect of depth and topography type using mixed effects models with the *nlme* package (Pinheiro Bates & R Core Team., 2023). Depth and topography type and their interaction were included as fixed, independent predictors. For all dependent variables, except pH, depth was included as an orthogonal quadratic polynomial term. Sampling location was included as a random factor to take the nested sampling design into account. The relationships between annual export of DOC and annual export of Fe and Pb were tested with linear regression including DOC and stream identity as independent variables. For the regression model with Pb as dependent variable there was a significant interaction, and the model was run separately for the two streams.

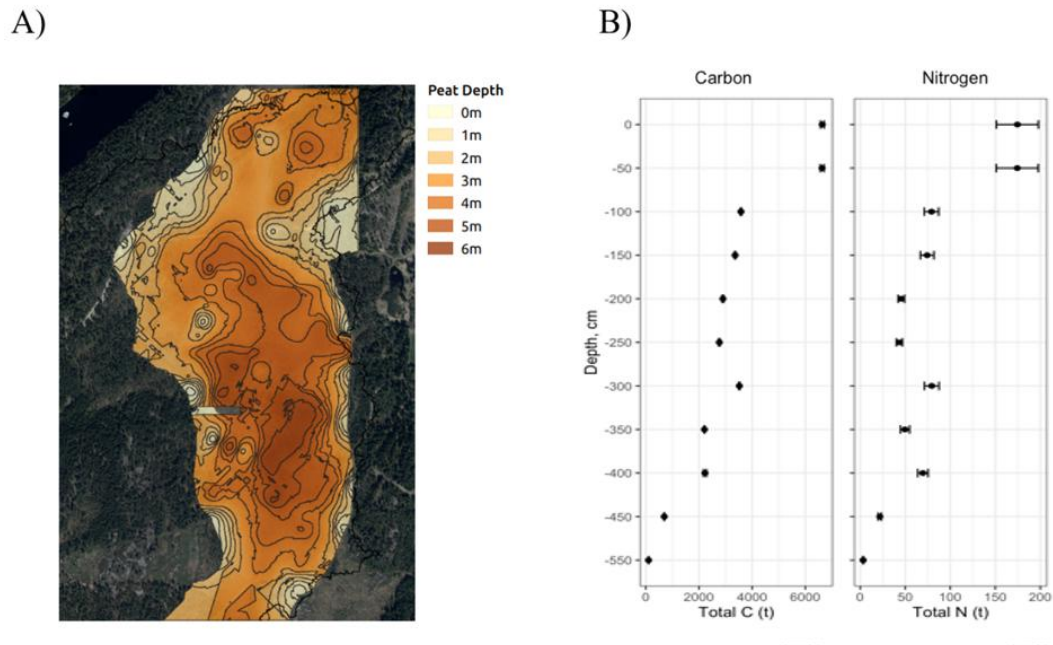
3 Results

3.1 Age, physical and chemical parameters of Mycklemossen mire

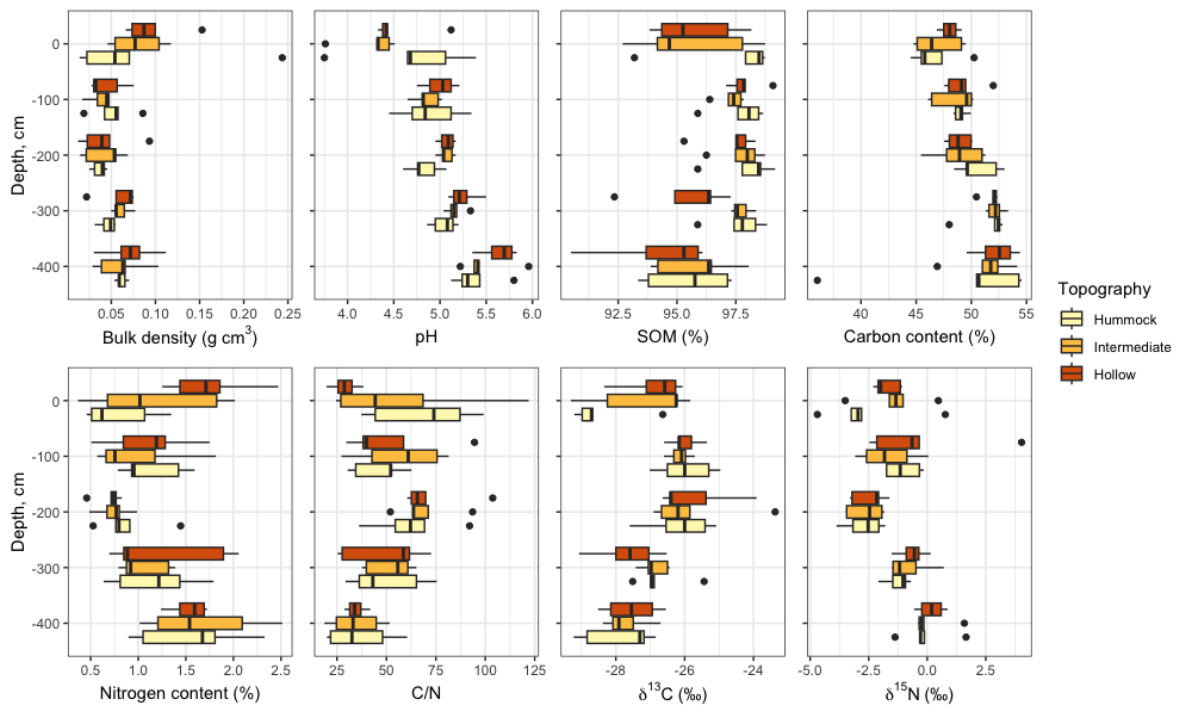
The maximum depth of Mycklemossen was about 600 cm (Fig. 2A) and the age of the mire centre was determined to be at least 3900 years by ^{14}C dating at 420-425 cm depth (Table S65). The total surface area of the mire was 0.23 km² in 2021. For the deepest part, the 550 – 600 cm depth interval, the area was only 0.0069 km² which is 0.03% of the total area. The total C pool of Mycklemossen was 34806 ± 1633.23 t of which 18% (6340 ± 4.76 t) were in the top 50 cm of the mire (Fig. 2B). The C and N pool declined to 1570 t ± 2.28 and 35 t ± 48 at 550-600 cm depth, respectively.

Physiochemical parameters were measured to a depth of 400 cm. Peat bulk density (g cm⁻³) significantly decreased with depth from 0.085 ± 0.023 at the surface to 0.04 ± 0.009 at 200 cm depth and then increased to 0.064 ± 0.011 to 400 cm (p = 0.001, Fig. 3, Table S76). The SOM content was above 90% at all depths and locations and highest in hummock. The SOM content for intermediate and hollow was lowest at the mire surface and at 400 cm depth, and highest at 200 cm depth (p = 0.04, Table S76). Peat pH was lowest at the mire surface and increased with depth from the surface to 400 cm depth, spanning from a pH of 4.5 ± 0.18 to 5.5 ± 0.11 (Fig 3). The increase in pH with depth was most pronounced for the hollow topography (p = 0.04, Fig 3, Table S76). Peat C content increased slightly with depth from around 47 ± 0.8 % at the top to 51 ± 1.9 % at 400 cm, while N content decreased from 1.27 ± 0.23 % in the surface of the mire to 0.78 ± 0.01 % in 200 cm depth and increased to 1.59 ± 0.21 % in 400 cm depth (p = 0.001, Table S76). The change in N with depth was less extreme for hummock compared to intermediate and hollow (p = 0.04, Fig 3, Table S76). Peat $\delta^{13}\text{C}$ increased from -27.5 ± 1.5‰ at the mire surface to -26.03 ± 0.74 ‰ at 100 cm depth followed by a decrease to -27.71 ± 1.22 ‰ at 400

cm depth ($p = 0.001$, Fig 3, Table S76). Peat $\delta^{15}\text{N}$ decreased from $-1.9 \pm 1.8\text{‰}$ at the surface to $-2.6 \pm 1.06 \text{‰}$ at 200 cm depth and then increased to $0.06 \pm 1.18 \text{‰}$ at 400cm depth ($p = 0.001$, Fig 3, Table S76).



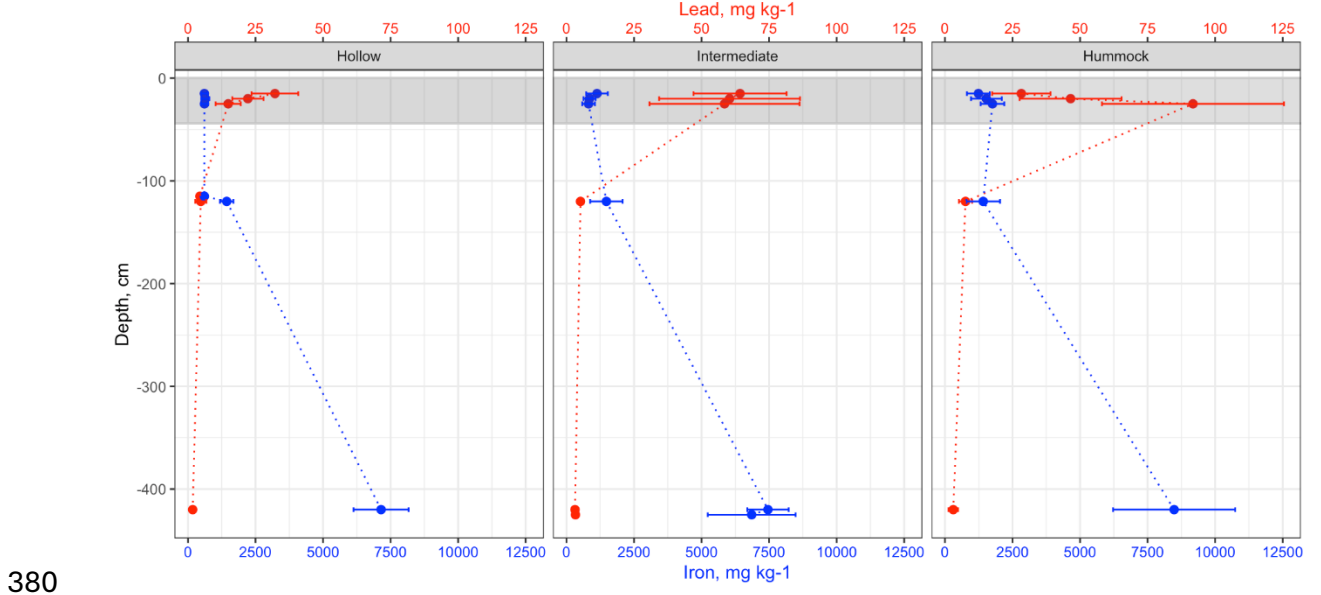
360 **Figure 2.** Spatial distribution of peat depth based on radar bathymetry (A) and total C and N pools in 50 cm depth increments (B) in Mycklemossen.



365 **Figure 3.** Peat properties in Mycklemossen. Peat samples in five locations and three topography types at 100 cm interval from the surface to 4 m depth. Box plots show the median value with the lower and upper quartile.

3.2 Spatial distribution of heavy metals and Fe in Mycklemossen

370 Peat Pb content was highest in the top of the mire and was essentially absent in peat samples at 420-425 cm depth (Fig. 4). Intermediate Hummocks generally had highest largest Pb content that, which was more than twice as high as for hollows, while the highest measurement of Pb content was measured in hummock at 25-50 cm depth. Specifically in hummocks, the Pb content increased from 28.26 mg kg⁻¹ in 15-20 cm depth to 91.8 mg kg⁻¹ in 25-50 cm depth (Fig 4, Table S2). In intermediate and hollow topographies Pb content was highest in 15-20 cm: 32.21 and 64.25 and 32.21 mg kg⁻¹ and decreased to 58.54 and 14.89 0.05 mg kg⁻¹ at 25-50 cm depth, respectively (p = 0.02, Fig 4, Table S78). Cadmium was essentially only found in hummocks in the top 50 cm, whereas As and Cr were present throughout the peat profile of the mire (Table S1). Peat Fe contentseentrations at the top of the mire were between 606 and 1237 mg kg⁻¹, which increased to between 1434 and 1474 mg kg⁻¹ in 120cm depth and barely changed until below 120 cm (Fig 4, Table S24).:- At 420-425 cm depth, Fe content was between 7147 and 8481 mg kg⁻¹ and contents were similar between topography types.



380 **Figure 4.** Pb (red) and Fe (blue) concentrations (mg kg⁻¹ DM) in peat at various depths of Mycklemossen. Points are means of 5 sampling locations and error bars are SE. Dotted lines are included for illustration only. Grey bands indicate the zone affected by water table fluctuations measured as absolute minimum and maximum water table depth during the period 2017- 2021. For statistics see Table S87.

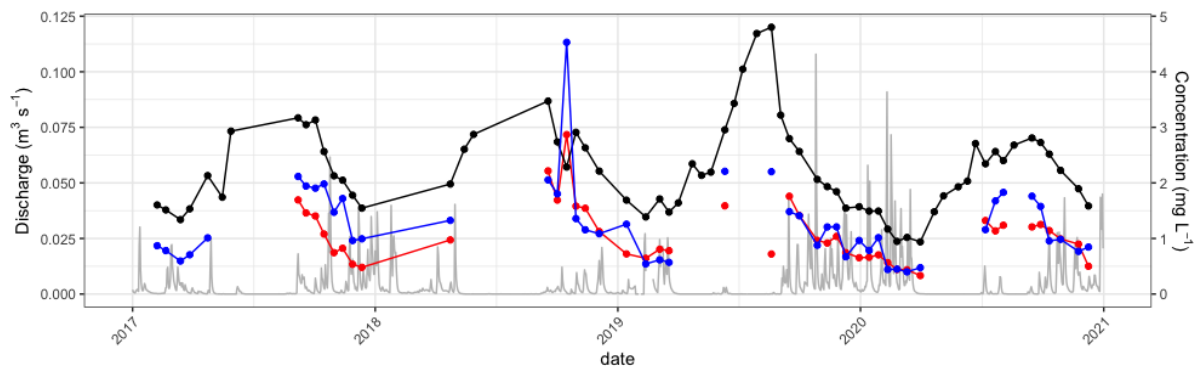


Figure 5. Stream discharge (grey), and water concentration of Fe (blue) and Pb x 200 (red) and C in DOC x 0.05 (black) from S1. Discharge shows daily averages of measurements made every 15 min, whereas concentrations in water were analysed from grab samples usually every 2-3 weeks during high flow and throughout 2019. Dots mark timing of sampling.

Data points for Fe and Pb were removed when discharge $< 0.0001 \text{ (m}^3 \text{ s}^{-1}\text{)}$, [which occurred during summer when the water level was too low to measure discharge, making calculation of export impossible.](#)

3.4 Export of DOC, Fe, and Pb from Mycklemossen and Ersjön Lake

During the period 2017 – 2020 the average annual ~~C export as~~ DOC [export](#) was [5834 kg](#) from the north part of Mycklemossen (S1) and 12616 kg leaving Ersjön (S6) ([Table S1](#)). The DOC export varied considerably between years [and](#) especially from Ersjön (Fig. 6). The highest DOC export from both Mycklemossen and Ersjön was in 2019, while the lowest export was in 2018. On average, annual DOC export from Ersjön in 2017 – 2020 was almost double of what it received from Mycklemossen, although this pattern was not consistent for individual years. In 2017 and 2018 DOC export from Mycklemossen and Ersjön was very similar, whereas in 2019 and 2020 export from S6 was around 3-fold higher than from S1. In 2017 –2020, the average annual Fe export was 150 kg from S1 and 325 kg from Ersjön (S6) ([Table S1](#)). The annual Fe export from Ersjön was therefore 215 % higher than the input from Mycklemossen. The average annual export of Pb was 0.705 kg from Mycklemossen and 0.681 kg from Ersjön ([Table S1](#)). -

Within streams, the inter-annual variation in Pb export followed the pattern of Fe and DOC. However, opposite to DOC and Fe, the export of Pb was only slightly higher from Mycklemossen than Ersjön. The annual export of DOC linearly correlated with annual Fe export in a similar way across the two streams ($p < 0.001$, $R^2 = 0.96$). DOC also linearly correlated with Pb, but the correlation slopes differed between streams ($p < 0.001$). Specifically, the annual DOC export in S6 was more than twice as high as the export from S1.

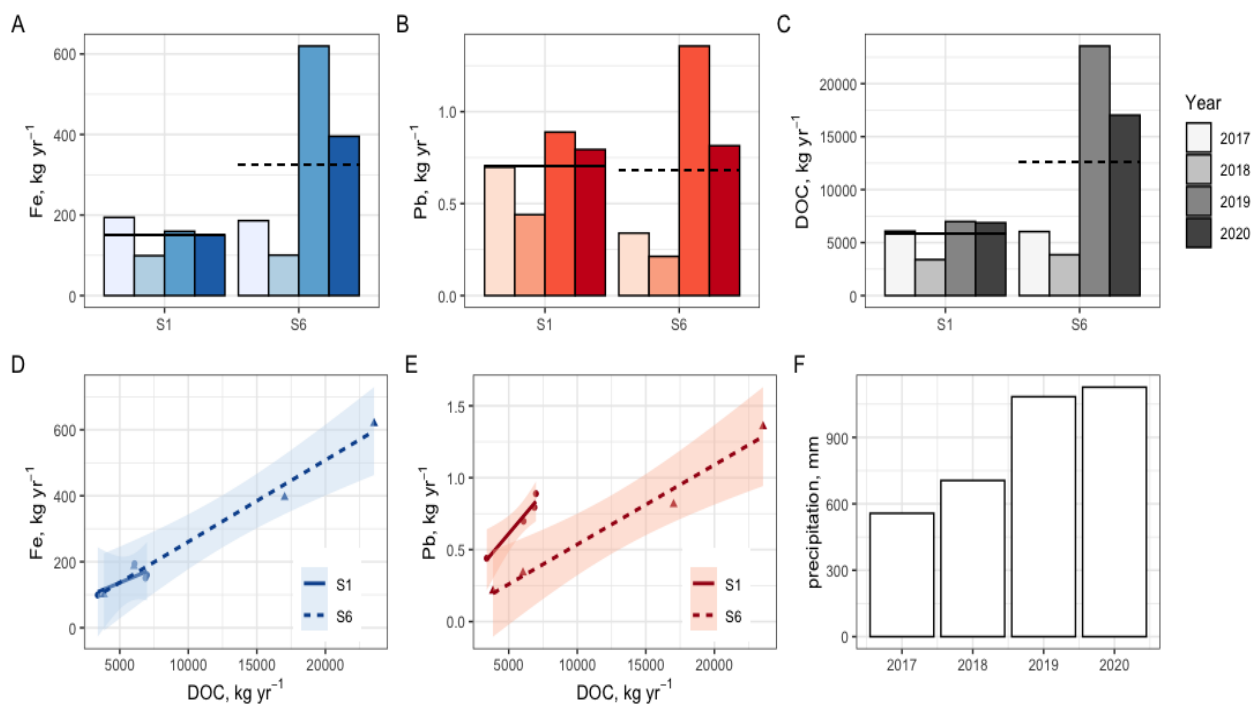
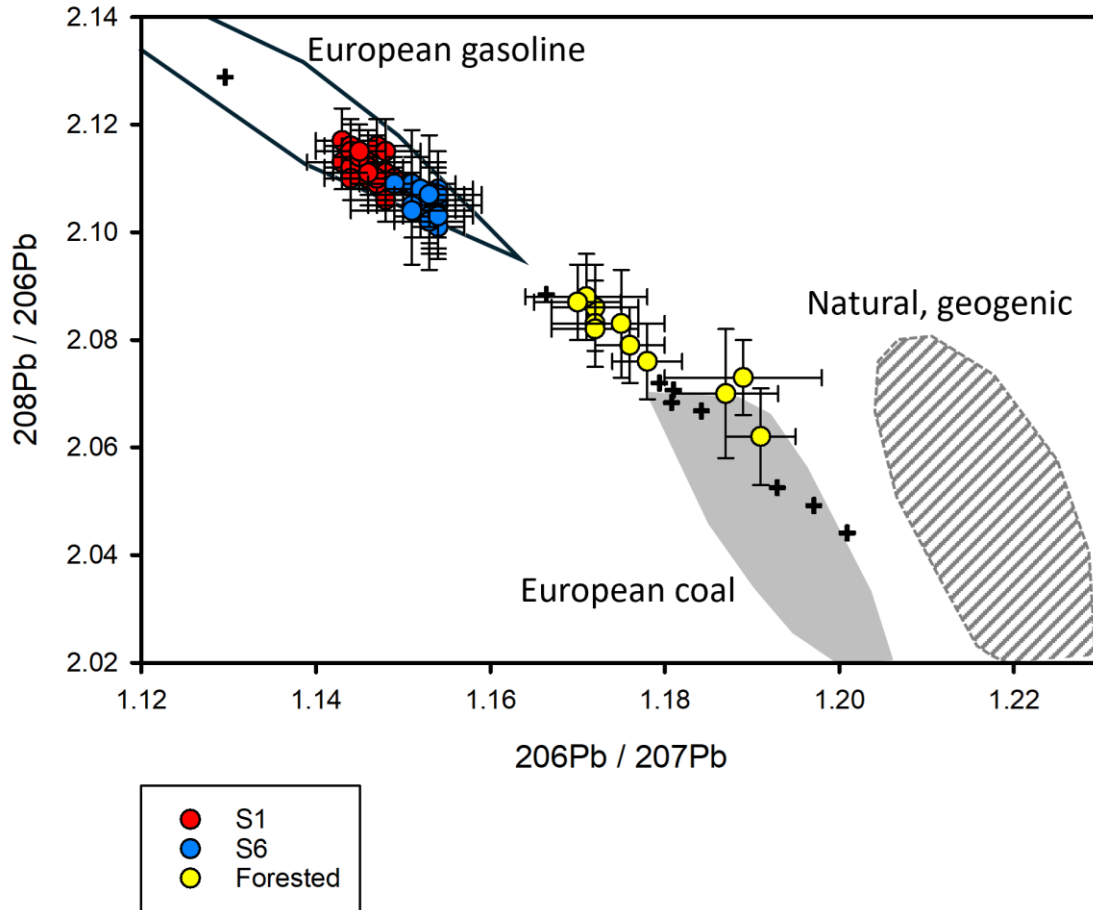


Figure 6. Annual export of DOC, Fe and Pb^{a†} from Mycklemossen to Ersjön lake (S1) and from Ersjön (S6) in 2017 to 2020 (A-C) and the linear relationship between export of DOC and export of Fe and Pb (D and E). Horizontal lines in bar chart are means of the years 2017-2020 in S1 (solid line) and S6 (hatched line). Note differences in scale between plots. Annual precipitation for the years 2017-2020 (F).

3.5 Pb isotopic composition

The Pb isotopic composition from the 57 water samples was analysed to determine whether the Pb exported from Mycklemossen and Ersjön was of anthropogenic origin (Table S89). The $^{208}\text{Pb}/^{206}\text{Pb}$ and $^{206}\text{Pb}/^{207}\text{Pb}$ composition from Mycklemossen (S1, $n = 25$), Ersjön (S6, $n=21$) and forested catchment (s12, $n = 11$) is plotted in figure 7, and for water leaving Mycklemossen, the $^{208}\text{Pb}/^{206}\text{Pb}$ ratio ranged between 2.106 ± 0.004 (2se) and 2.117 ± 0.006 (2se) and has a weighted mean ratio of 2.11175 ± 0.00095 ($n=25$, MSWD = 1.4). The $^{206}\text{Pb}/^{207}\text{Pb}$ ratio ranged between 1.143 ± 0.004 (2Se) and 1.150 ± 0.003 (2Se) and a weighted mean ratio of 1.1460 ± 0.0008 ($n=25$, MSWD = 1.5). For the water leaving Ersjön, the $^{208}\text{Pb}/^{206}\text{Pb}$ ratio ranged between 2.101 ± 0.005 (2Se) and 2.109 ± 0.010 (2Se) with a weighted mean ratio of 2.10690 ± 0.0014 ($n=21$, MSWD = 0.6). The $^{206}\text{Pb}/^{207}\text{Pb}$ ratio was between 1.149 ± 0.004 (2Se) and 1.154 ± 0.004 (2Se) with a weighted mean ratio of 1.1527 ± 0.0009 ($n=21$, MSWD = 0.4). For the forested neighbouring catchment, the $^{208}\text{Pb}/^{206}\text{Pb}$ ratio was between 2.062 ± 0.009 (2Se) and 2.088 ± 0.008 (2Se) with a weighted men ratio of 2.08010 ± 0.0046 ($n=11$, MSWD = 3.8). For the $^{206}\text{Pb}/^{207}\text{Pb}$ ratio, it ranged between 1.170 ± 0.005 (2Se) and 1.191 ± 0.004 (2Se) with a weighted mean of 1.1778 ± 0.0052

430 (n=11, MSWD = 9). [The isotope mixing model revealed that Mycklemossen contributed by \$84.2 \pm 2.6\%\$ of the total Pb load to Ersjön \(S6\), despite the much lower total annual discharge \(Table S1\).](#)



435 **Figure 7.** Lead isotope composition of water from S1, S6 and forest land at Skogaryd Research Catchment, overlying an isotope plot of different Pb sources (redrawn from [Komárek et al., 2008](#) (Komárek et al., 2008)). Crosses represent the isotopic composition of marine antifouling ([data from Jeong et al., 2023](#)) ~~paint~~ ([data from Jeong et al. 2023](#)).

440

4 Discussion

Peatlands are crucial global C stores, but subjected to ~~anthropogenic~~ climate change that threatens the future stability of this C stored as peat (Zhong et al., 2020). Stored metals from natural and anthropogenic sources could become mobilised when climate change promotes peat degradation. Here we aimed to document the size, age and total C content of a northern European mire representing mires in the temperate and boreal transition zone and investigate the pools and export of DOC, Fe and Pb. Specifically, we wanted to investigate the ~~export/transport~~ of Fe as an important metal influencing peat stability and to document the Pb pollution status in the mire and a downstream lake. We found clear indications that ~~during~~ warm and dry periods with higher peat degradation followed by precipitation that re-established hydrological connectivity between mire and lake, ~~metals were most important for~~ ~~were~~ release and export of Fe, Pb and DOC ~~together with DOC into the downstream ecosystem~~. Below, we discuss the context, magnitude and consequences of these findings.

4.1 ~~Mycklemossen~~ Assessment of decomposition and C stability ~~C stores and stability in relation to oxygen and Fe in Mycklemossen~~

The peat in Mycklemossen was dated to 3900 years in 4 m depth and is thus likely closer to 6000 years in the mire centre at almost 6 m deep. This is within the age range of mires in Sweden (Ehnvall et al., 2024). However, Mycklemossen is in the younger end of the range and seems to have accumulated peat at a faster rate compared to other Swedish mires (Andersson & Schoning, 2010; Hansson et al., 2024). The difference in dominant vegetation of hollow and hummock likely control the difference in C to N ratio of the top layer, as hummock was mostly dominated by vascular plants (*Eriophorum vaginatum*, *Calluna vulgaris* and *Erica tetralix*) and the hollows mainly consist of different *Sphagnum* species as *S. rubellum*, *S. fallax* and *S. austinii* as well as *Rhyncospora alba* (Kelly et al., 2021). The higher C to N ratio in hummocks are likely due to higher lignin content from the vascular plants, as *Sphagnum* does not contain lignin (Biester et al., 2014; Weng & Chapple, 2010; Zeh et al., 2020). This effect was also reflected in the $\delta^{13}\text{C}$ in the top layer, with slightly more ^{13}C depletion at the hummock with *Calluna vulgaris* than hollow with *Sphagnum* dominance (Biester et al., 2014). Furthermore, The depth profile of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ partly reflects the changing age of the peat. However, we only observed minor changes (a few permilp). Plant sourced C near the surface is more ^{13}C depleted nowadays than before the beginning of the industrial age ('the Suess effect') (Drollinger et al., 2019; Esmeijer-Liu et al., 2012). The increasingly depleted $\delta^{13}\text{C}$ signature in the deepest peat layers follows the pattern of the decreasing C to N ratio and likely reflects increasing degree of degradation with depth (Smeds et al., 2025). Below the top layer and the

water table (8-25 cm depth; Rinne et al., 2022) in the permanently anaerobic zone, the slightly higher ^{13}C enrichment may also reflect methane production activity as methanogens discriminate against ^{13}C , which consequently enriches the peat in ^{13}C (Keane et al., 2021; Krull & Retallack, 2000). Further down, the decreasing C to N ratio likely reflects increasing degree of degradation with depth as C is removed (Biester et al., 2014; Smeds et al., 2025). While the ^{15}N enrichment increased with depth, reflecting discrimination during peat decomposition (Biester et al. 2014), the ^{13}C on the other hand ~~increased~~ decreased with depth. This latter can be explained by climatic changes/variation during the Holocene, in particular changes in soil moisture which in turn affects photosynthetic ^{13}C discrimination and consequently peat ^{13}C (Kumar Das et al., 2024; Nykänen et al., 2020).

The Fe content in the peat increased about 10-fold from the top ~~to the bottom~~ of the mire to 400 cm depth, supporting that Fe in the Mycklemossen is primarily sourced from bedrock and groundwater and to a small extent from deposition (Steinnes et al., 2005). 18% of ~~the~~ Mycklemossen C pool was in the top 50 cm, partly because of the large mire area at this depth interval and a higher peat bulk density in the top one meter of the mire. This part of the mire was exposed to oxic conditions during summers, which makes a large part of the ~~peat~~ mire C susceptible to decay (Fenner & Freeman, 2011). However,

static oxic conditions during summer could also stabilise peat and DOC through adsorption and complexation interactions with Fe (Riedel et al., 2013; Song et al., 2022; Wang et al., 2017), though most Fe in Mycklemossen is placed in deep anoxic peat layers. Nevertheless, Fe-OM complexes are formed in both oxic and anoxic peat (Bhattacharyya et al., 2018). The stabilising effect of Fe might therefore not be limited to the oxic layer. However, in the presence of oxygen, oxidative reactions catalysed by Fe can lead to production of hydroxyl radicals that can promote degradation of peat (Qin et al., 2022; Trusiak et al., 2018). Such reactions might be driven by small concentrations of Fe (between 280 - 2.300 mg kg⁻¹ peat; (Curtinrich et al., 2024), which is within the range of Fe measured in the top part of Mycklemossen. In the top part of Mycklemossen mire, there might therefore be both stabilising and destabilising reactions with Fe taking place, but it is unclear how important the destabilising reactions contra the stabilising reactions is for peat stability and mire C dynamics. Static oxic conditions during summer could also stabilise peat due to and complexation interaction with oxidised Fe (Chen et al., 2020; Song et al., 2022), though most Fe in Mycklemossen is placed in deep anoxic peat layers, and therefore the stabilising effect of Fe on peat C might be limited. However, regardless of redox regime, the majority of total Fe in peat is interacting with OM, and Fe-OM complexes can also be found in anoxic peat (Bhattacharyya et al., 2018).

On the contrary (Qin et al., 2022; Trusiak et al., 2018), the C destabilising mechanism of Fe can be driven even by small concentrations of Fe (2.3 mg g^{-1} peat), which is much lower than the content in the top part of Mycklemossen (Curtinrich et al., 2022).

4.2 Export of ~~FeDO~~ and ~~DOCFe~~ downstream of Mycklemossen

Iron exhibited strong and linear correlations with DOC in the streams from Mycklemossen (S1) and Ersjön (S6). The average ratio between DOC and Fe of 0.03 in both S1 and S6 is the same as the median ratio value reported for Fe and DOC ratios in Swedish lakes from a national investigation (Weyhenmeyer et al., 2014) (Weyhenmeyer et al., 2014). The Fe-DOC export relationship in the mire-lake complex of Mycklemossen and Ersjön is therefore likely representative for the rest of Sweden. The ~~export pattern of strong correlation between export of~~ Fe and DOC was ~~as expected in line with previous studies~~ (Broder & Biester, 2017; Chauhan et al., 2024; Knorr, 2013), ~~compared to downstream catchments that is also supplied with DOM from forested catchment and to higher degree with microbial DOM. The DOC leaving Mycklemossen and Ersjön was most likely not of the same composition, with the DOC from the mire expected to be contain a higher degree of polyphenolic compounds~~ (Kaal et al., 2017). ~~Despite that, the correlation correlation of Fe and DOC export was very similar in S1 from Mycklemossen and S6 from Ersjön, which could indicate the type of DOC was not important for explaining the correlation of Fe and DOC export in the studied mire-lake complex. Instead (Neubauer et al., 2013) (Björnerås et al., 2021; Knorr, 2013) drought, precipitation and hydrological connectivity isare generallye accepted as the main controlling processes for mobilisation and export of DOC, Fe and Pb in peatlands (Broder & Biester, 2015, 2017; Prijac et al., 2023), which seems to be the case for the studied mire-lake complex too. . It seems to be most clear from the concentration data of DOC, Fe and Pb that was highest in late summer and autumn after a drought period and where discharge measurements became available again indicating re-establishment of hydrological connectivity.~~

The year of 2018 that was the warmest and driest year with the least precipitation during the study period, gave further insight into the controlling mechanisms of DOC, Fe and Pb export in the mire-lake complex. DOC production is highest under oxic conditions when the water table is low (Fenner & Freeman, 2011; Strack et al., 2008) and at high temperatures (Rosset et al., 2022). Thus, the notably warm and dry year of 2018, where the mire was exposed to oxic conditions for the longest period (Fig. S2) could therefore be expected to yield the

highest DOC production also leading to the highest export of DOC together with Fe and Pb considering the strong correlations presented (Fig. 6). However, the lowest export of DOC, Fe and Pb from Mycklemossen was measured in 2018, while the highest exports were measured in 2019 and 2020. This likely emphasizes the influence of precipitation and hydrological connectivity, as the years 2019 and 2020 had around to 2-fold more precipitation compared to 2017 and 2018 (Fig. 6), which likely increased the water table enough to allow higher discharge from the mire (Clark et al., 2007; Koehler et al., 2009; Prijac et al., 2023). Looking at the stream concentrations of DOC, Fe and Pb, there was an unexpected asynchronous peak with the highest concentrations of Fe and Pb measured in 2018 (Fig. 5), while the highest DOC concentration was measured in 2019. Even though the stream DOC concentration was lower in 2018 than 2019, the DOC production was likely highest in 2018 due to a long period with low water table levels (Fig S2). Interestingly, this relationship was not seen in the year of 2018, which was the warmest and driest year, with the least precipitation. DOC production is highest under oxic conditions when the water table is low (Fenner & Freeman, 2011; Strack et al., 2008) and at high temperatures (Rosset et al., 2022). Especially the notably warm and dry year of 2018, where the mire was exposed to oxic conditions for the longest period (Fig. S2) could therefore be expected to yield the highest DOC and Fe export. However, the lowest export of DOC and Fe from Mycklemossen was measured in 2018, while the highest exports were measured in 2019 and 2020. The same pattern goes for the concentrations of DOC and Fe. This probably emphasizes the influence of precipitation and hydrological connectivity, as the years 2019 and 2020 had around to 2 fold more precipitation compared to 2017 and 2018 (Fig. 6), which likely increased the water table enough to allow discharge from the mire (Clark et al., 2007; Koehler et al., 2009; Prijac et al., 2023). Looking at the stream concentrations of DOC and Fe as well as Pb, there was an unexpected asynchronous peak with the highest concentrations of Fe and Pb measured in 2018 (Fig. 5), while the highest DOC concentration was measured in 2019. Even though the stream DOC concentration was lower in 2018 than 2019, the DOC production was likely highest in 2018 due to a long period with low water table levels (Fig S2). A possible explanation, but lack of hydrological connectivity prevented DOC to leave the mire (Broder & Biester, 2015, 2017; Prijac et al., 2023). for the low stream DOC concentration in 2018 could be because microbes had better conditions to mineralize the DOC. The hydrologic disconnectivity is also indicated by pH values in S1 during summer much higher than the mire pH (Fig. S2). The water in S1 was during the dry summer periods not flowing and likely affected by the immediate surrounding of the stream. The water leaving Ersjön via S6, had higher DOC export in the two wetter years, likely due to increased precipitation and discharge (Clark et al., 2007; Koehler et al., 2009; Rosset et al., 2019). In support of that, Fe, Pb and DOC in every year peaked after a drought period when the water table depth increased to a level

565 ~~allowing discharge measurements (Rosset et al., 2020). In general, we found that export of DOC and Fe from Mycklemossen seemed to be more affected by hydrological connectivity than warmer temperatures and oxic conditions. At the same time, the formation of labile DOC and Fe is likely highest under oxic condition. This is supported by soil respiration measurement at Mycklemossen, which were substantially higher in the year of 2018 compared to other years (Keane et al., 2021), which is indicative for higher microbial decomposition. The higher decomposition, which is likely the main mobilisation process of Fe and Pb in the top part of bogs (Broder & Biester, 2017), could also explain why the highest Fe and Pb concentrations were measured in 2018 as more Fe and Pb would have been mobilised from the peat. In general, it seemed that export of DOC and Fe from Mycklemossen was mostly affected by hydrological connectivity, while ~~than~~ warmer temperatures and oxic conditions probably was most important for mobilisation.~~

570 One point this study could not address, is whether longer periods of drought, despite not increasing DOC export from Mycklemossen, increased the overall C loss through increased mineralization under oxic conditions (Fenner & Freeman, 2011).

575 4.3 Pb in Mycklemossen

In agreement with other studies, we observed highest Pb content in the top 50 cm which then dropped and reached a non-detectable content below 120 cm depth in all topographies (Klaminder et al., 2006; Nieminen et al., 2002). ~~(Klaminder et al., 2006; Nieminen et al., 2002). This indicates that Pb was deposited onto Mycklemossen via wet and dry deposition. Peat in hummock was too young to date with ¹⁴C at 20-25 cm and was likely younger than the ban of lead.~~ Hummock forming species have higher biomass production rates (Malmer & Wallén, 1999) ~~(Malmer & Wallén, 1999), but typically and degrades slower compared to hollow species, which is generally due to a higher content of recalcitrant components as lignin-like compounds and secondary metabolites in hummock~~ (Limpens et al., 2017; Mäkilä et al., 2018; Turetsky et al., 2008). This is supported by the higher SOM content and N content in the top of the mire compared to hollow (Fig 3). Under the assumption that the hummock and hollow topographies have remained stable at least since the start of anthropogenic pollution (Nungesser, 2003), a slower decomposition of hummock material could be what lead to a higher accumulation of Pb in the part of Mycklemossen in hummock compared to hollow. ~~Peat in hummock was too young to date with ¹⁴C at 20-25 cm and was likely younger than the ban of lead.~~

Thus, it is likely that new hummock material formed on top of the polluted layer during the last few decades since Pb was banned from gasoline and antifouling paint, explaining why the highest concentration of Pb was measured in 25-50 cm depth in hummocks and not in 15-20 cm depth. The observed local differences in Pb content might lead to differences in peat decomposition depending on topography.

Also, hummocks are more wind exposed and therefore might be more prone for accumulating Pb compared to intermediate and hollow topographies. However, the higher Pb concentrations in hummock compared to intermediate and hollow topographies should also be seen in the light of their younger ages at 20-25 cm depth. This might lead to local differences in Pb and heavy metal toxicity on peat decomposition in peatlands depending on topography.

Pb-Lead is toxic for mosses (Choudhury & Panda, 2005) and hampers the growth of microbial communities associated with *Sphagnum fallax* (Nguyen-Viet et al., 2007) (Nguyen-Viet et al., 2007). Lead contents of 80 – 300 mg kg⁻¹ soil can affect microbial decomposition of C and nutrient turnover (Bååth, 1989; Zheng et al., 2017) and above 70 mg kg⁻¹ can alter bacterial community composition (Hu et al., 2007). The Pb content of 92 mg kg⁻¹ in hummocks at 25-50 cm depth in Myklemossen are thus likely to affect the microbial community and the biomass turnover rate. The studies Nguyen-Viet et al., 2007, Bååth, 1989 and Zheng et al., 2017 reports effects of Pb based on contents (mg kg⁻¹) and not bioavailable Pb. Therefore, the high Pb content measured in hummock in this study, could have a potentially harmful effect on microbes (Lu et al., 2025). The bioavailability of Pb can be assessed in different ways, but requires some form of bioassay (Fleming et al., 2013; Hoang et al., 2025). In peatlands, Pb is mostly found strongly bound to organic matter and minerals with a low available fraction and is generally very immobile due to high binding affinity for organic matter-OM (Lu et al., 2025; Novak et al., 2011; Vile et al., 1999). The bioavailable Pb in hummock is therefore certainly lower than the 92 mg kg⁻¹, but Pb can be made available by microbial decomposition and accumulate in organisms over time. Most studies that report toxic effects of Pb on microbial decomposition, perform experiments in periods of weeks or months, but toxicity of Pb increases with exposure time (Connell et al., 2016) (Connell et al., 2016). Therefore, the toxic effect of Pb could be more severe in long term *in situ* decomposition studies. In that regard, interestingly, hummock *Sphagnum* species associated with hummock commonly decompose slower than hollow species under the same environmental conditions, but to which extent contents of Pb, or other heavy metals, content could affect play a role in their lower decomposability has not previously been considered (Bengtsson et al., 2016; Johnson et al., 1990; Johnson & Damman, 1991) (Bengtsson et al., 2016; Johnson et al., 1990; Johnson & Damman, 1991). In Myklemossen, we only detected contents of Pb exceeding the toxicity threshold in hummocks. Decomposition experiments of with

peat was not tested in this study, but different pollution loads between topographies and local degradation dynamics might be necessary to understand Pb cycling in mires exposed to Pb [pollutiondeposition](#).

625 4.4 Pb pollution [status in](#) stream [water waters and pb export](#)

The concentration of Pb in stream water from Mycklemossen, was up to 10-fold higher compared to streams from pristine Siberian bogs located 200 km from anthropogenic sources of heavy metals (Kharanzhevskaya et al., 2023)([Kharanzhevskaya et al., 2023](#)), and slightly lower compared to a bog in Germany exposed to pollution from a nearby shooting range (Broder & Biester, 2015)([Broder & Biester, 2015](#)). The average Pb concentrations in stream water from Mycklemossen in the period of 2017 to 2020 was 4-fold higher than the long-term accepted values of $1.2 \mu\text{g L}^{-1}$ and suggests that this stream, according to European standards, is of bad environmental quality (Sjöberg, 2016)([Sjöberg, 2016](#)). [In stream water from Ersjön, the concentration of Pb was drastically lower \(\$1.1\pm 0.1 \mu\text{g L}^{-1}\$ \), and can be considered good quality for long term exposure \(Sjöberg, 2016\).](#)

The highest concentration of Pb in stream water from Mycklemossen was measured in late 2018 and reached $14 \mu\text{g L}^{-1}$, which is the short-term maximum limit value for fresh water (Sjöberg, 2016). [As already pointed out, the high Pb concentration in S1 \(\$14 \mu\text{g L}^{-1}\$ \) in 2018 was likely due to a higher degree of Pb mobilisation \(Broder & Biester, 2017\). Beside the European standard for Pb thresholds, a comprehensive analysis taking bioavailability into account and including 7 European surface water scenarios and 25 freshwater species, found Pb toxicity thresholds to within \$6.1\$ and \$31 \mu\text{g L}^{-1}\$ \(Van Sprang et al., 2016\). Therefore, Pb reached concentrations on short-term basis that can be considered potentially harmful for freshwater fauna. Furthermore, it seems ~~In stream water from Ersjön, the concentration of Pb was drastically lower \(\$1.1\pm 0.1 \mu\text{g L}^{-1}\$ \), and can be considered good quality for long term exposure \(Sjöberg, 2016\).~~\(\[Van Sprang et al., 2016\]\(#\)\)\(\[Broder & Biester, 2015\]\(#\)\)that longer periods of drought in a future climate could lead to higher mobilisation of Pb and stream water concentrations of Pb exceeding toxicity thresholds \(Szkokan-Emilsson et al., 2013\).](#)

645 [4.5 Export and fate of Pb in the mire-lake complex](#) The $14 \mu\text{g L}^{-1}$ Pb concentration was measured in 2018 after a long drought period where the lowest water table depth was also measured. Just as for Fe and DOC, the highest Pb concentrations were measured after a drought period when the water table depth increased to a level allowing discharge measurements. Longer periods of drought and more extreme rain events in a future climate might therefore increase heavy metal export from polluted peatlands (Souter & Watmough, 2016; [Szkokan Emilsson et al., 2013](#)).

655 While twice as much Fe and DOC was exported from Ersjön through S6 compared to S1 leaving Mycklemossen, which roughly follows differences in catchment size, -the export of Pb ~~was~~ere similar between the two streams in the period 2017 to 2020. At the same time, about 2-fold more Pb per amount of DOC left S1 compared to S6. The~~The~~ main explanation is probably found in how Pb in the two streams were sourced. The expected $^{206}\text{Pb}/^{207}\text{Pb}$ ratio in the area around Skogaryd is in the range of 1.245-1-326 (Reimann et al., 2012), which is higher than the data from Mycklemossen of 1.146. The value at Mycklemossen is at the lowest end for Northern Europe (Reimann et al., 2012) and is indicative for anthropogenic pollution (Fig. 7). For the $^{208}\text{Pb}/^{206}\text{Pb}$ ratio the average value of 660 2.112 for Mycklemossen is close to the median for Northern Europe (Reimann et al., 2012). Generally, ~~the~~ Pb isotope ratios~~analysis~~ revealed that Pb in S1 and S6 primarily was sourced from gasoline (Fig. 7), but the Pb isotopic signature in S6 was slightly shifted towards the signature of forest soil which overlaps with European coal, marine anti fouling paint and natural geogenic sources. As isotope signature of marine antifouling paint falls on the mixing line of geological and gasoline Pb, its contribution is unclear. Ersjön also receives water from other 665 land-uses (forest) within its catchment, which could be dominated by natural Pb isotopes, which supplies Pb to S6 at lower concentrations than S1. Except for one sampling, the $^{208}\text{Pb}/^{206}\text{Pb}$ ratio is always lower in Erssjön than Mycklemossen, indicating that the forest land almost always contributes to the lead in Erssjön. No previous estimates of the water residence time have been made but given the size of the Ersjön (6.2 ha) and the mean depth of 1.7 meters ~~{Citation}~~ (Milberg et al., 2017) the volume would be ~100 000 m³, which gives a mean residence 670 time of about 3 months. Conducting mixing model on the individual sampling dates (N=10), Mycklemossen contributed by 68 – 100% to the lead in Erssjön outflow. Furthermore, the mixing model showed that around 1933% of the Pb coming from Mycklemossen was retained in Ersjön, indicating that Ersjön acts as a sink for the Pb from Mycklemossen. Thus, the similar Pb export from S1 and S6 is likely explained by an additional Pb input from the forested catchment to S6 of a lower concentration than what Mycklemossen supplies, and 675 sedimentation/retention of Pb in Ersjön, which we estimated to be around 0.132 kg yr⁻¹.

Conclusion

680 Here, we investigated a mire-lake complex inland from the west coast of Sweden subjected to recent climate change and exposed to heavy metal pollution. We wanted to characterize the mire in terms of physiochemistry,

age and total C content and evaluated ~~the pools and the~~ export of Fe and Pb in relation to DOC in the light of future climate. We showed that export of Fe, ~~Pb~~ and DOC ~~downstream~~ from a nutrient poor mire located in temperate and boreal transition zone is sensitive to climate. The mobilisation of Fe, Pb and DOC from the mire was seemingly affected by drought and thus decomposition, while the export mainly was controlled by hydrological connectivity. Furthermore, the release of Fe and DOC from the mire was most likely affected by drought conditions while the export was controlled by hydrological connectivity. The ratio between Fe and DOC demonstrated strong linear correlations in stream water from both the mire and lake, which indicated that transport of Fe and DOC ~~was~~ tightly ~~connected~~ connected. Our investigation of Pb in the mire-lake complex showed that Pb pollution from gasoline had resulted ~~in concentrations~~ potentially toxic ~~concentrations to microorganisms,~~ specifically in the hummock topography and in downstream water ~~waysways. Peaks in DOC, Fe and Pb stream water concentrations occurred at increased discharge after a drought period, which showed that both Fe and Pb transport was connected to DOC, and thus degradation of peat. As such, low water table provide conditions suitable for labile DOC production while increase in water table depth promotes DOC export.~~ In a future climate with longer periods of drought and higher occurrence of heavy rain events, export of DOC and metals will likely increase from Mycklemossen and similar mire ecosystems. This study highlights that mires in anthropogenically exposed areas not only store C, which upon release will cause positive feedback to the climate, but also that this ~~decomposition/gradation~~ is linked to an environmental risk ~~of~~ the local environment in the form of heavy metal ~~pollution/pollution.~~

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Data availability

705 Author contributions

J~~Tomas~~ Thomsen: Conceptualization, Investigation, Methodology, Writing – original draft, Writing - review & editing. **S~~Ligne~~ Lett**: Conceptualization, Investigation, Formal analysis, Methodology, Visualization, Writing – original draft, Writing - review & editing, Supervision. **L~~Keif~~ Klemedtsson**: Conceptualization, Investigation, Formal analysis, Methodology, Resources, Writing - review & editing. **D~~elia~~ Rösel**: Methodology, Formal analysis, Writing - review & editing. **L~~ouise~~ Rütting**: Conceptualization, Investigation, Methodology, Writing - review & editing. **K~~atja~~ Salomon-Johansen**: Conceptualization, Supervision, Funding acquisition, Writing - review & editing. **T~~obias~~ Rütting**: Conceptualization, Investigation, Formal analysis, Funding acquisition, Resources, Writing - review & editing.

715

Competing interests

The authors declare that they have no conflict of interest

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