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The Contribution of Boreal Wetlands to the Northern Hemisphere Carbonyl Sulfide Sink

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Abstract Carbonyl sulfide (COS), a gas used as a tracer in carbon cycle studies, has a potential missing sink in Northern high latitudes. Boreal COS budgets typically account for the contribution by forests, but ignore any uptake that wetland ecosystems, widespread in Northern latitudes, may contribute. The first direct measurements of the ecosystem-atmosphere COS exchange of a boreal wetland, presented here, demonstrate their likely importance for Northern latitude COS budgets. The investigated wetland (Siikaneva, Finland) took up on average 11 pmol m^{-2} s^{-1} COS, which was c. 72% of the nearby boreal forest COS uptake. During nighttime, the COS uptake rates were similar at both sites. Upscaling our measurements to the boreal region using the Organizing Carbon and Hydrology In Dynamic Ecosystems model revealed a Northern wetland sink of c. 13 Gg S/y, changing the simulated budget from a small source to a COS sink impacting Northern latitudes carbon uptake estimates based on COS.

Plain Language Summary Carbonyl sulfide (COS) is a gas used to study the carbon cycle because plants absorb it in a similar way as they absorb carbon dioxide. However, to use COS effectively, all sources and sinks must be understood and nowadays there still is an unexplained missing sink in high northern latitudes. Budget calculations of COS in boreal regions typically look at the contribution of forests, but not of wetlands. We measured COS fluxes over a boreal wetland, compared them to COS fluxes measured over a nearby forest and upscaled the fluxes to estimate their contribution to the boreal region and to verify if boreal wetlands can account for the missing sink. With our measurements we show the importance of including boreal wetland COS fluxes in budget calculation.

Key Points:

- Carbonyl sulfide (COS) sink measured at a boreal wetland was about 3/4 of that at a nearby forest
- Both the boreal wetland and the forest COS fluxes were driven by light with similar nighttime fluxes
- Upscaling wetland fluxes with Organizing Carbon and Hydrology In Dynamic Ecosystems shifted the model from COS source to sink changing Northern latitudes carbon estimates

Supporting Information:

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

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1. Introduction

Carbonyl sulfide (OCS or as further used here: COS) is the most abundant sulfur-containing trace gas in the atmosphere. Recently, interest in COS has grown as it is thought to play an important role in understanding the atmosphere-biosphere exchange of carbon dioxide (CO_2) and its responses to climate change as an indicator for the gross primary productivity (GPP) and stomatal conductance (g_s) (Asaf et al., 2013; Berry et al., 2013; Sandoval-Soto et al., 2005). The challenge of the partitioning of the net CO_2 flux into GPP and respiration (Wohlfahrt & Galvagno, 2017) does not occur for COS. While COS co-diffuses with CO_2 and encounters similar resistances during the uptake process, COS differs from CO_2 as it is taken up irreversibly by plants through the light-independent enzyme carbonic anhydrase (Notni et al., 2007; Protoschill-Krebs & Kesselmeier, 1992; Protoschill-Krebs et al., 1996). Consequently, there is practically a one-way COS flux directed into the leaf, making it a promising molecule to study the GPP (Kooijmans et al., 2017). Moreover, COS fluxes can help estimate the g_s, as it represents a key resistance in regulating COS exchange (Seibt et al., 2010; Wehr et al., 2016; Yang et al., 2018).

According to the latest atmospheric COS budget (Ma et al., 2024; Remaud et al., 2023) the two main COS sources are anthropogenic emissions (Zumkehr et al., 2018) and oceanic emissions (Kettle et al., 2002; Lennartz

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et al., 2017) and the main sink is the above-mentioned uptake by vegetation (Berry et al., 2013; Sandoval-Soto et al., 2005). The magnitude of these three components is however highly uncertain, resulting in a non-closed global budget (Ma et al., 2021; Montzka et al., 2007; Whelan et al., 2018). Recently Remaud et al. (2023) evaluated the atmospheric COS budget by comparing observations against simulated concentrations of COS of several transport models. Since the model-observations mismatch was greater than the model spread, they were able to demonstrate that there was a missing sink in the high Northern Hemisphere (NH). This was confirmed by two inverse studies using two different transport models (Ma et al., 2023). Since there are not enough atmospheric measurements to disentangle the source contributions in the NH, this could come from an overestimated oceanic source and/or an underestimated terrestrial carbon sink (Remaud et al., 2023).

Underestimation of the COS uptake by the high NH may arise from the fact that land surface models such as the "Simple Biosphere Model version 4" (SiB4) and the "Organizing Carbon and Hydrology In Dynamic Ecosystems" (ORCHIDEE) models, neglect COS sources/sinks from wetlands. In ORCHIDEE, wetlands are assumed to behave as anoxic soils (Abadie et al., 2022; Kooijmans et al., 2021), which act as COS sources. SiB4, on the other hand, does not distinguish between anoxic/oxic soils and thus neglects wetlands (Kooijmans et al., 2021).

Assessing the importance of the NH wetland contribution for global budget calculations is difficult, since so far measurements of wetland COS fluxes are available mostly from salt marshes, which, driven by salinity, typically act as COS sources (Whelan et al., 2013). In contrast, freshwater marshes and bogs act as smaller sources or even sinks due to plant uptake. But wetland plants can also become COS sources by transporting the gas produced in the soil to the atmosphere (Whelan et al., 2018). Furthermore, we have to regard the boreal wetlands as a complex (symbiotic) mixture of higher plants surrounded by cryptogamic mixtures of vegetation with contributions by living and dead material as well.

Here we propose that the missing COS sink in Northern latitudes is partly due to a lack of data and the omission of wetland COS fluxes in global budget calculations. To test this hypothesis, we conducted COS flux measurements over a boreal wetland for the period May till September 2019 and compare these against flux measurements made at a nearby evergreen needleleaf forest site. We compare the main drivers and magnitude of the COS fluxes at both sites and use these data to upscale the wetland fluxes in the NH with the ORCHIDEE model to address the relevance of the inclusion of wetland COS fluxes in global budget estimations.

2. Materials and Methods

The Siikaneva wetland (61.83265°N, 24.19285°E, 160 m ASL) is a oligotrophic (nutrient poor) fen (ICOS, 2017) located close to the Hyytiälä SMEAR II station (Figure S1 in Supporting Information S1). The vegetation is dominated by peat mosses (*Sphagnum spp*. with *S. papillosum*. as main species), sedges and Rannoch-rush (*Scheuchzeria palustris*), the topography is flat. This fen is spatially homogeneous and extends around 100 m toward the east and west and 200 m to the north and south (Rinne et al., 2018).

The Hyytiälä boreal forest (61.84741°N, 24.29477°N, 182 m ASL) (ICOS, 2018) is located approximately 5 km from the wetland (Figure S1 in Supporting Information S1). The vegetation consists mostly of Scots pines (*Pinus sylvestris L.*). More detailed information about this site can be found in Vesala et al. (2022).

The measurement campaign on the wetland lasted from May till September of the year 2019. The forest data used for comparison covers the same months for the years 2013–2017 and was measured and processed as elaborated in Vesala et al. (2022).

The eddy covariance (EC) flux data, was measured with an ultrasonic anemometer (Gill-HS-50, Gill Instruments Ltd., England, UK), while COS, CO_2, water vapor (H_2O) mixing ratios were measured with an Aerodyne quantum cascade laser spectrometer (Aerodyne Research Inc., Billerica, MA, USA). Both instruments were operated at a frequency of 10 Hz and fluxes were averaged over 30 min. More details on the experimental setup can be found in Vesala et al. (2022) for the forest site. The instrumentation used at the Siikaneva wetland was identical, measurement height was 3 m, the length of the gas inlet tube c. 5 m and flow rate c. 8 L min^{-1}.

The site-specific environmental variables photosynthetically active radiation (PAR), air temperature, relative humidity (RH), vapor pressure deficit (VPD), water table depth (WTD) and precipitation for the measurement period were taken from the SmartSMEAR online database (https://smear.avaa.csc.fi/) (Aalto et al., 2019). These were compared to long term monthly means (1981–2010 for air temperature and precipitation (Pirinen

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et al., 2012) and 2002–2010 for RH and VPD from the Finnish Meteorological Institute (Finnish_Meteorological_Institute, 2022) (https://en.ilmatieteenlaitos.fi/download-observations) and 2001–2010 for PAR from SmartSMEAR all measured at Hyytiälä to verify if the meteorological circumstances during the measurements period were similar to the long term conditions. Precipitation data is represented as monthly sums only when more than 95% of data was available.

All fluxes were processed with the EddyUH software (Mammarella et al., 2016) as described in Kohonen et al. (2020) and Vesala et al. (2022) (further details in Supporting Information S1).

In order to identify the major drivers of the COS exchange, random forest (RF) regressions were calculated on the 30 min flux data with the python package *sklearn.ensemble* (parameters chosen with "*GridSearchCV*" and evaluated based on out-of-bag (OOB) score, cross-validation, mean squared error and mean residuals, 500 estimators, 300 minimal samples, and 42 random states, bootstrap).

The Moods' median test (python package "*scipy.stats.median_test*") was used to determine the degree of independence between the medians of the wetland and forest data set.

Due to data-availability/quality, 77% of the wetland data and 44% of forest data was missing. These gaps were equally distributed over diurnal- and seasonal cycle. Gaps were filled following the response of the COS uptake to PAR, a major driver of short-term variability in COS fluxes (Kohonen et al., 2020), using a Michaelis-Menten-type relationship with an offset (Equation 1).

$$\mathrm{FCOS} = \left(\frac{a * \mathrm{PAR}}{\mathrm{PAR} + b}\right) + c \tag{1}$$

Parameters a, b, and c are free and were determined using the python non-linear least squares function "*scipy.optimize.curve_fit*." Corresponding parameters for the wetland data are: $a = -6.12 \pm 1.14$, $b = 251.86 \pm 115.74$, $c = -8.28 \pm 0.43$ and for the forest; $a = -16.5 \pm 0.43$, $b = 154.6 \pm 16.1$, and $c = -8.0 \pm 0.26$. A t-test confirmed that the gap-filling does not introduce a systematic bias, however gap-filling underestimates the spread of the data with R^2 values of 0.45 and 0.60 for the wetland and forest data, respectively. When calculating the daily median to compute the seasonal cycle from this parametrization, the R^2 score is 0.23 and 0.50 for the wetland and forest, respectively, while for the diurnal cycle the R^2 score is 0.90 and 0.99 for the wetland and forest data, respectively.

Given that COS is known to be consumed by hydrolysis in soil water, one might expect this uncatalyzed process to be responsible for a larger share of the net uptake at the wetland compared to the forest site. To explore this contribution we thus estimated the magnitude of the uncatalyzed COS uptake at both sites using equations put forward by (Ogée et al., 2016) (see Supporting Information S1). These uncatalyzed uptakes rates were then compared against the observed nighttime COS uptake, when plant (catalyzed) uptake is minimal, in order to obtain a maximum estimate of the contribution of hydrolysis to the net ecosystem COS uptake.

Upscaling the measured COS fluxes was done with the ORCHIDEE land surface model (Krinner et al., 2005) for the years 2015–2019 using the measured median COS fluxes for the period April-September and zero flux the rest of the year. Representations of vegetation COS uptake (Maignan et al., 2021) and soil COS exchanges (Abadie et al., 2022) were implemented in ORCHIDEE, based on the model from Berry et al. (2013) and Ogée et al. (2016), respectively. Consequently, the ecosystem COS fluxes measured in this study were compared to the ones simulated in ORCHIDEE. In the model, the contributions of oxic and anoxic soils to soil COS exchanges were differentiated. ORCHIDEE simulations were conducted at a 0.5° spatial resolution with outputs at a monthly temporal resolution. Additionally, seasonal variations were modeled. More information can be found in Supporting Information S1.

3. Results

3.1. Environmental Parameters

Since measurements at the wetland took place in 2019 and at the forest from 2013 to 2017, we first compared the environmental conditions during the measurement period with the long-term (1981–2010) climatic conditions in the measurement region. Overall, the measurement years were not different from the long-term conditions nor did the measurement year at the wetland differ significantly from the measurement years at the forest (Figure S2 in

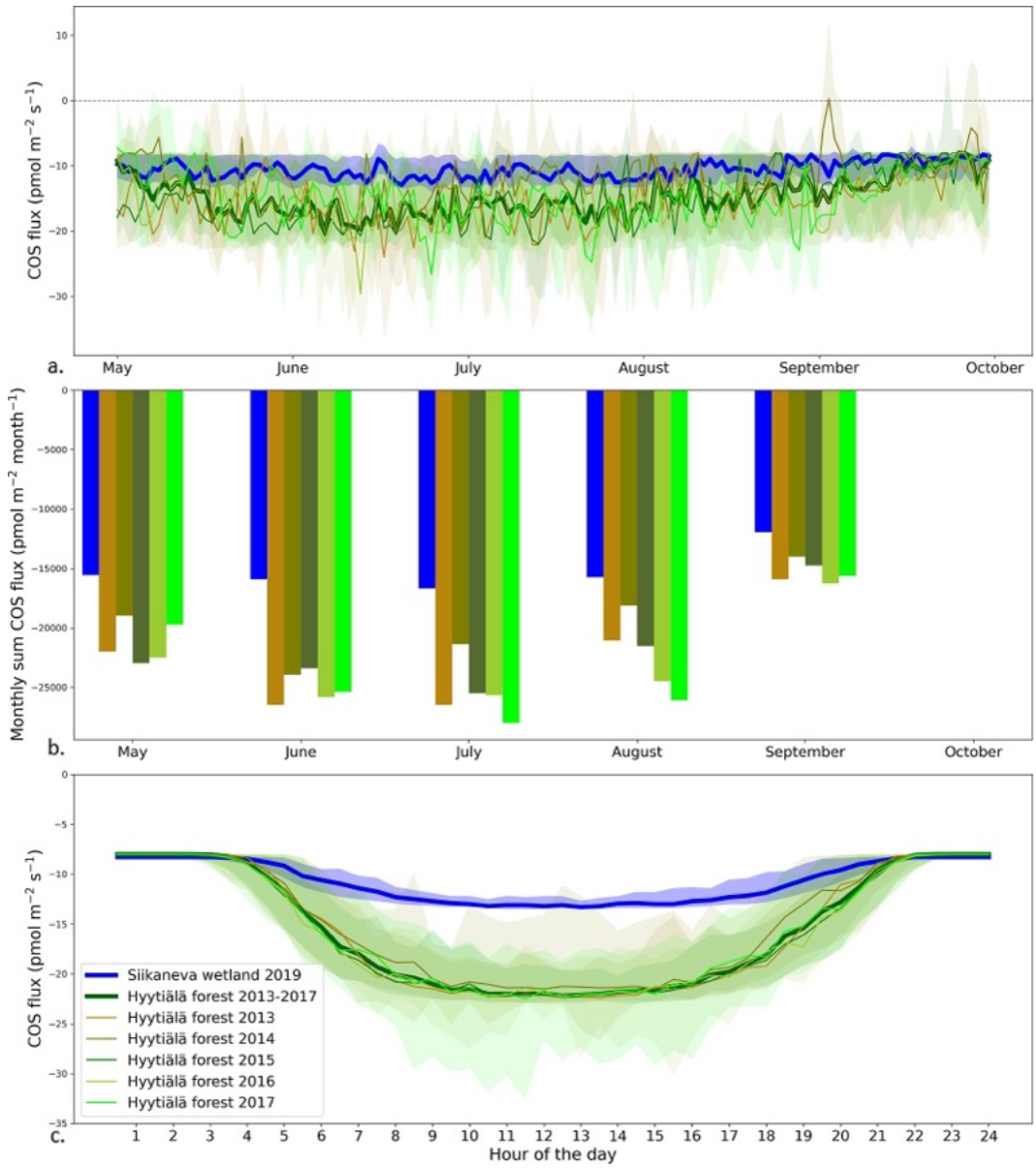

Figure 1. (a) Daily median gap-filled carbonyl sulfide (COS) fluxes with 25 and 75 percentiles. (b) Monthly sums of gap-filled COS fluxes. (c) Mean diurnal cycle of gap-filled COS flux with 25 and 75 percentiles. Blue for Siikaneva wetland and green variations for Hyytiälä forest. COS sink reported as negative flux.

Supporting Information S1). An exception was precipitation, which varied among measurement periods. For example, June was a drier month at the wetland and a wetter month at the forest compared to the long-term mean precipitation (Figure S2e in Supporting Information S1).

Leaf area index (LAI) differed substantially between the two sites. At the wetland, the all-sided LAI was estimated to be in the range of 0.18–1.2 and 1.18–2.2 when including the mosses. In the forest, all-sided LAI was in the range of 6.5–7 with similar values for all the years except 2017, which had slightly lower median LAI values (data not shown).

3.2. COS Fluxes

The seasonal median gap-filled COS flux of the wetland was −10.6 pmol m^{-2} s^{-1}, with a 25%–75% percentile range between −12.8 and −8.3 pmol m^{-2} s^{-1} (Figure 1a and Table S1 in Supporting Information S1). This was

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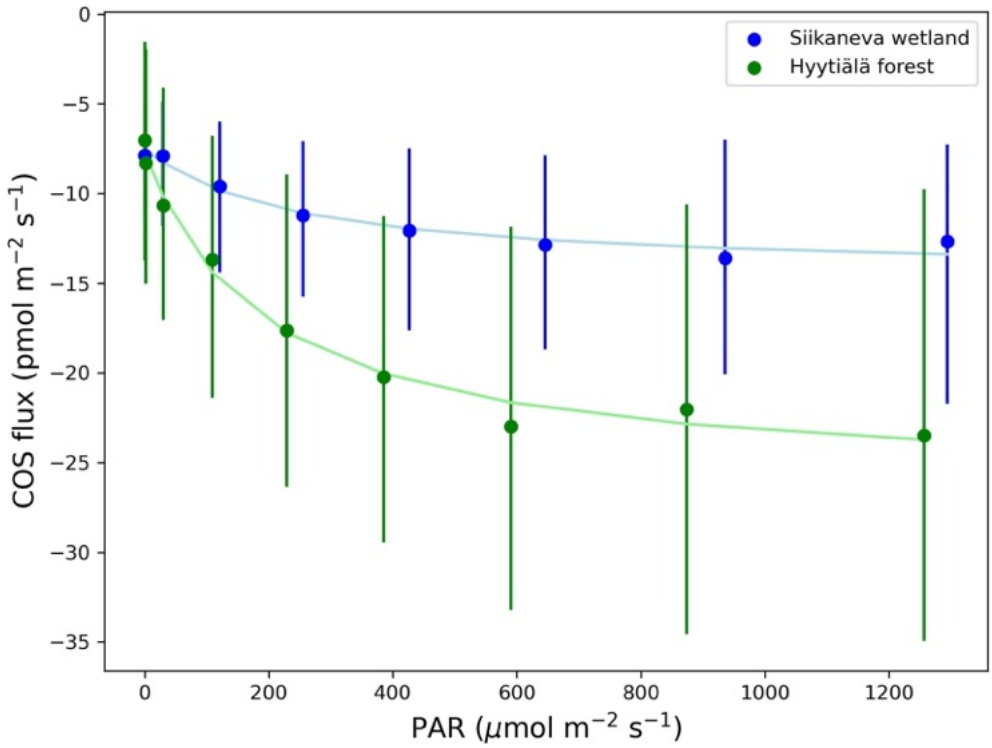

Figure 2. Carbonyl sulfide flux relationship with photosynthetically active radiation (PAR). Siikaneva wetland in blue and Hyytiälä forest data in green. Data is collected in 10 equally sized bins. Error bars represent 25 and 75 percentiles. Regression equations: $y = ((-6.9*\mathrm{PAR})/(\mathrm{PAR} + 241)) - 7.5$ for the wetland and $y = ((-19*\mathrm{PAR})/(\mathrm{PAR} + 190)) - 7.6$ for the forest.

significantly (p-value < 0.001) less negative than the flux measured at the forest in the period May-September 2013–2017, which had a gap-filled seasonal median value of −14.7 pmol m^{-2} s^{-1}, with a 25%–75% percentile range between −21.5 and −8.0 pmol m^{-2} s^{-1}. The wetland COS flux was around 72% of the forest COS flux.

On a monthly timescale, the wetland fluxes remained remarkably stable throughout the analyzed period compared to the COS fluxes found in the forest, where the sink strength tends to peak in June/July (Table S1 in Supporting Information S1 and Vesala et al. (2022)). This is also illustrated in Figure 1b showing monthly sums of the gap-filled fluxes. Notably, the wetland fluxes remained fairly constant over the large range of WTD variation (more than 20 cm) during the dry summer months with days characterized by high temperatures compared to mean air temperature of the analyzed period (Figure S3 in Supporting Information S1).

Both sites exhibited a clear diurnal cycle with similar minimum COS fluxes during nighttime (−8.28 and −8.01 pmol m^{-2} s^{-1} for the wetland and forest, respectively) and maxima around noon (−13.26 and −22.20 pmol m^{-2} s^{-1} at the wetland and forest, respectively), resulting in a 3 times larger diurnal flux amplitude at the forest (Figure 1c).

The nighttime abiotic hydrolysis of COS at the wetland ranged between 0.018 and 0.12 pmol m^{-2} s^{-1}, corresponding to 0.2% and 1.5%, respectively of the median measured nighttime COS uptake flux, while at the forest the abiotic hydrolysis was almost half that of the wetland (Text S3 in Supporting Information S1). This demonstrates that the net ecosystem uptake of COS is dominated by plants.

The drivers of the COS fluxes were identified with RF regression analysis, resulting in PAR to be the outstanding main driver for the COS exchange at both sites (feature importance 0.93 and 0.80 at the wetland and forest, respectively), followed by air temperature at the wetland and RH at the forest (Table S2 and Figure S4 in Supporting Information S1).

The light response curves (Figure 2) were consistent with the diurnal cycles (Figure 1c). Both show similar offset/nighttime fluxes (−7.5 pmol m^{-2} s^{-1} for the wetland and −7.6 pmol m^{-2} s^{-1} for the forest), a lower maximum

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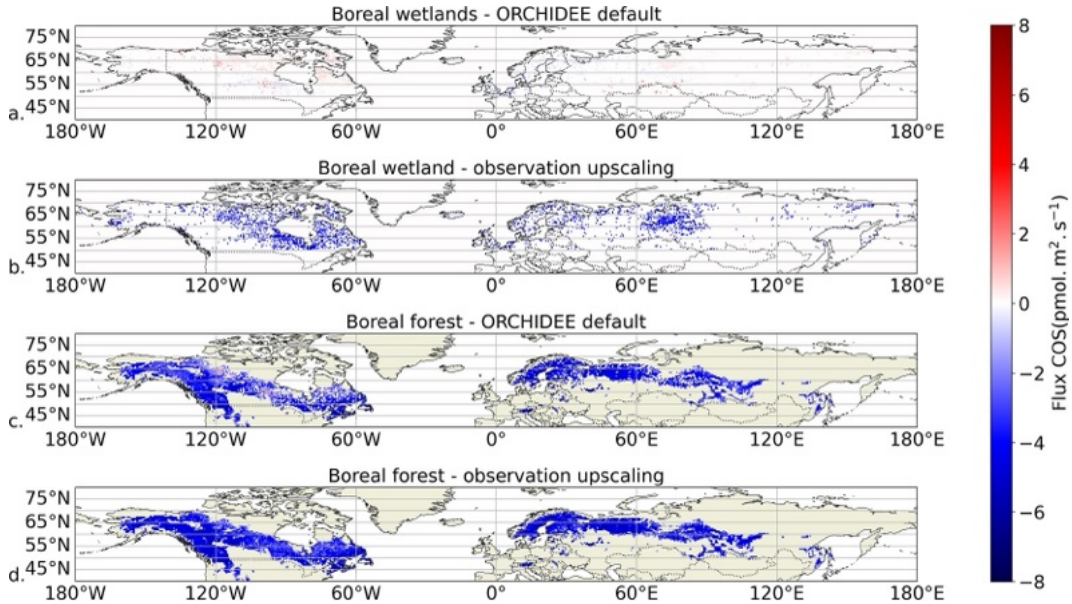

Figure 3. Organizing Carbon and Hydrology In Dynamic Ecosystems (ORCHIDEE) simulations. In (a, c) the default boreal ORCHIDEE output for the wetland/forest carbonyl sulfide (COS) fluxes and in panels (b, d) the fluxes calculated based on the measured median wetland/forest COS flux.

COS uptake reached at the wetland compared to the forest (theoretical infinite PAR limit going toward −14.4 pmol m^{-2} s^{-1} for the wetland and −26.6 pmol m^{-2} s^{-1} for the forest). Moreover, the lower maximum is reached at a lower light level at the wetland compared to the forest suggesting a lower PAR-saturation threshold at the wetland, consistent with the flatter diurnal cycle. Indeed, the light level at which 90% of the maximal uptake is reached, was lower at the wetland (c. 914 μmol m^{-2} s^{-1}) than at the forest (c. 1,167 μmol m^{-2} s^{-1}).

3.3. Model Upscaling

The ORCHIDEE model in the boreal wetland area had a default COS budget of 0.36 Gg S/y (i.e., net emission resulting from opposing vegetation uptake and anoxic soil emission) (Figure 3a). Upscaling the measured seasonal median wetland COS flux resulted in a budget of −13.32 Gg S/y, that is, net COS uptake, with a 25%–75% percentile range of −16.09 and −10.43 Gg S/y, respectively (Figure 3b). This represents c. 13.4% of the missing sink in the NH (c. 99 Gg S/y) and c. 27.5% of the missing sink in the 50°N–70°N region (c. 48 Gg S/y) (both missing sinks calculated with data from Ma et al. (2021)).

For the boreal forests we looked at areas with at least 25% of boreal evergreen needleleaf forests, which gave a default budget of −36.29 Gg S/y in the ORCHIDEE model (Figure 3c). With our measured median forest COS flux the resulting budget was −44.81 Gg S/y with a 25%–75% percentile range of −56.22 and −33.56 Gg S/y, respectively, that is, a factor of c. 1.25 stronger sink (Figure 3d) and gives a degree of uncertainty between the default model parametrization and our upscaling, since ORCHIDEE is well tuned to the Hyytiälä forest (Abadie et al., 2023).

The impact of adding COS sinks from evergreen boreal forests and wetlands was assessed globally by comparing the simulated and the observed latitudinal gradients. The global COS atmospheric concentrations simulated by the LMDz Atmospheric Transport Model were similar to the standard model concentrations in terms of annual mean gradient. Around 60°N the new updated simulated concentrations remained overestimated (Figure S6c in Supporting Information S1).

4. Discussion

Since previous research proposed a missing COS sink in the NH, but boreal wetland contributions were overlooked, we investigated if a reevaluation of the NH wetland COS fluxes could explain this gap. The potential net COS sink of northern wetlands is expected as vegetated boreal and arctic peatland acts as net carbon sink (Ramage

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et al., 2024; Virkkala et al., 2021). COS fluxes were measured over one vegetation period at a boreal wetland and compared to 5 years of vegetation period measurements at a nearby forest. These COS fluxes were then upscaled to the NH with the ORCHIDEE model to test our hypothesis.

4.1. Wetland COS Flux

Our study found the boreal wetland to be a COS sink over the measurement period. This novel finding challenges previous literature representing these ecosystems mainly as sources of COS (Li et al., 2006; Whelan et al., 2013, 2018). Our contrasting finding can be explained by the studied wetland type, being a freshwater wetland covered by mosses and vascular plants, which greatly contribute to the measured COS uptake, while earlier wetland studies focused on marshes where COS emission is favored by salinity (Whelan et al., 2018). Moreover, we measured wetland COS fluxes directly using the EC technique. Early studies, using chamber enclosures, often used sulfur-free sweep air, possibly biasing results toward emission (Whelan et al., 2018).

4.2. COS Flux Comparison Between Sites

The inferred COS sink was weaker at the wetland than at the forest, most likely due to ecosystem differences. On a diurnal timescale, the comparison between the sites showed similar nighttime COS fluxes, while the diurnal cycle showed a larger amplitude for the forest compared to the wetland (Figure 1c). The different daytime uptake, driven by PAR (Figure 2), found at both locations most likely can be explained by the larger forest Leaf area index (LAI) (6.5–7 m^2 m^{-2}) compared to the wetland LAI (1.18–2.2 and for only vascular plants 0.18–1.2 m^2 m^{-2}). The higher LAI in the forest enables more COS uptake compared to the wetland, while the presence of mosses at the wetland, which can release COS during daytime (Gimeno et al., 2017), reduces the net sink strength at the wetland. Moreover, the larger LAI of the forest likely compensates for any, per unit leaf area, lower g_s of the evergreen needleleaf forest compared to the wetland plant species, which, due the unlimited water supply, can afford higher g_s (Buckley, 2019; Lambers et al., 2019). A lower g_s at the forest compared to the wetland was also found in earlier studies who looked at g_s estimated from the evapotranspiration (Alekseychik et al., 2018; Launiainen et al., 2016), where the wetland showed 2–3 times higher g_s than the forest. A similar ratio was found between the sites when dividing the maximum COS uptake by the mean LAI (data not shown). Additional support for the dominant role of LAI in determining the differences in COS uptake, derives from the different shapes of the light response curves (Figure 2). At leaf level, g_s is typically tightly coordinated with photosynthesis (Ball et al., 1987) and increases linearly with increasing PAR followed by a saturation at higher PAR values. Due to the low leaf area, the light response of the wetland's COS uptake resembles the one of a single leaf with a clear saturation. Since a large fraction of the forest's leaf area is shaded due to the larger LAI, leaves experience lower PAR values not sufficient for saturation. As PAR increases, an increasing fraction of shaded leaf area shifts from the linear to the saturation part of the light response and thus at ecosystem scale, saturation of the COS uptake is reached more gradually (Knohl & Baldocchi, 2008). Finally, the complexity of the wetland ecosystem including microbial processes should be acknowledged. Mosses appear to release COS during daytime conditions as shown by Gimeno et al. (2017). Moreover, similarly to COS release in freshwater through photochemical production and in salt water marshes (Du et al., 2017; Whelan et al., 2018), COS emission from the wetland water should be considered. The ample presence of water at the wetland site caused a larger uncatalyzed uptake of COS (Ogée et al., 2016) compared to the forest site, however its magnitude (<1.5%) was small compared to plant-mediated uptake.

Interestingly, during nighttime, both sites took up similar amounts of COS, suggesting that the high LAI of the forest might be compensated by a lower minimum g_s (Dawson et al., 2007) as coniferous trees like *P. sylvestris*, which covered most of the forest EC footprint, have a low g_s compared to wetland species (Miner et al., 2017). Additionally, part of the wetland nighttime COS uptake can be attributed to the mosses prevalent at the site, as found by Gimeno et al. (2017). Mosses were abundant also at boreal forest floors but they contribute a minor fraction to the GPP as mosses are smaller the older the forest is (Kulmala et al., 2011) and over the boreal biome, mosses can generate only 1/3 of the vascular plant GPP for the same normalized difference vegetation index (Yuan et al., 2014).

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4.3. Model Upscaling

The default ORCHIDEE LSM implementation simulated wetlands as a net source, resulting from anoxic soil release overwhelming any plant uptake, whereas we show with the implementation of our measurements, boreal wetlands to be a COS sink (Figures 3a and 3b and Figure S6 in Supporting Information S1), substantially contributing (c. 13.4%) to the missing sink in the NH and even more significantly to the boreal region (c. 27.5%).

The difference in default model output and the output when using the measured forest fluxes was less pronounced (Figures 3c and 3d and Figure S6b in Supporting Information S1). On a global scale and especially compared to the magnitude of the inferred missing NH sink (calculated with data from Ma et al. (2021)), the simulated wetland contribution was small (Figure S6a in Supporting Information S1), indicating that additional sinks are required in the NH to close the budget. Further experimental measurements are required to that end, covering multiple full years and different locations (both NH as SH), which will also help to better understand the carbon cycle, especially in the boreal region, which is heavily impacted by ongoing climate change (Cooper, 2014). Moreover, for comparison and validation, other LSM such as SIB4, which also underestimates the COS NH sink (Remaud et al., 2023), could be tested on our data set.

The biggest limitation of the upscaling, which was intentionally simplified, likely is the use of the median COS flux and the assumption that all northern wetlands behave similarly.

The main boreal wetland types in the BAWLD domain with their percentage of total wetland area are bogs (28%), permafrost bogs (27%), fens (29%), marshes and swamps and differentiate based on their moisture levels, hydrodynamics, nutrient status and pH (Olefeldt et al., 2021). In the region and season analyzed in this paper, 50°N–70°N, permafrost is marginal (Ran et al., 2021). The difference between bogs and fens lies especially in plant cover (bogs covered mostly by peat moss, while nutrient rich fens can facilitate higher plant growth) and pH (bogs more acid than fens) (Albrecht, 2023). The increased vascular plant cover on nutrient rich fens most likely leads to more COS uptake during light than on bogs or nutrient poor fens. The higher pH at the nutrient rich fens will increase uncatalyzed COS uptake (Figure S5 in Supporting Information S1), which this study however demonstrated to be overall negligible. Therefore, our assumption to upscale the investigated nutrient poor fen, will probably lead to an underestimation of the potential boreal wetland COS sink.

Moreover, we assumed wetlands to act as net COS sink during May till September and during the other months the flux was set to zero due to a lack of winter data. This assumption is supported by Vesala et al. (2022), who measured close to zero COS fluxes on a snow-covered boreal forest, and the wetland being covered by snow during winter.

5. Conclusions

This study measured ecosystem-scale COS fluxes over a boreal wetland revealing it to be a COS sink with similar nighttime fluxes to a nearby forest, while the amplitude of the diurnal cycle was around 3 times higher at the forest, mainly due to differences in vegetation. Upscaling the measured fluxes with the ORCHIDEE LSM changed the default wetland budget from being a small COS source to a considerable sink. This study thus reveals the relevance of the inclusion of boreal wetland measurements for the NH COS budget calculations. While showing the importance of including wetland ecosystems in budget calculations, a missing COS sink in the NH persists. More measurements of COS fluxes over boreal ecosystems and inclusion of detailed wetland types in land surface models can help close the COS budget and increase the understanding of the carbon cycle and its responses to climate change.

Data Availability Statement

The data used for this article is available at Zenodo (de Vries, 2024).

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