

Boreal Peatland 24-hour Solar-induced Chlorophyll Fluorescence Measurements under Continuous Daylight Conditions during the Summer Period

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Abstract

Continuous ground-based observations of solar-induced chlorophyll fluorescence (SIF) from northern peatlands remain uncommon, despite their potential to complement ecosystem carbon flux measurements and support satellite-based monitoring of vegetation activity. Here, we present continuous SIF estimates using data acquired with the Fluorescence Box (FloX) at two boreal peatland sites in northern Finland during the 2023 and 2025 growing seasons. SIF was retrieved using the Bayesian SIFFI algorithm, and the analysis focuses on the diurnal and seasonal variability of spectrally resolved and spectrally integrated fluorescence signals. The measurements capture complete 24-hour cycles under Arctic summer daylight conditions, providing a unique dataset for investigating peatland photosynthetic dynamics. The results reveal clear diurnal and seasonal variability in SIF and show consistent temporal patterns with ecosystem CO₂ exchange measured with the eddy covariance technique. Although retrieved SIF accuracy decreases under very low illumination conditions, the observations demonstrate the potential of continuous SIF measurements to support studies of peatland carbon cycling and highlight the importance of continued ground-based SIF monitoring for the interpretation and validation of satellite SIF observations in view of the upcoming ESA FLEX mission.

1. Introduction

Peatlands are wetland ecosystems that are characterized by the accumulation of partially decomposed organic matter and represent an important terrestrial carbon store, particularly at Boreal and Arctic regions (Gorham, 1991, Yu et al., 2010). Therefore, they play an important role in the global carbon cycle. The amount of carbon stored in peatlands depends on the balance between carbon uptake by vegetation and carbon release through decomposition of organic matter. Arctic peatlands are sensitive to changes in climatic and environmental conditions, including for example permafrost thaw (Sim et al., 2021, Hugelius et al., 2020), increasing air temperatures (Crichton et al., 2025, Handley et al., 2026), and drought (Fenner and Freeman, 2011). As the Arctic has warmed nearly four times faster than the global average during recent decades (Rantanen et al., 2022), ongoing changes in temperature, permafrost conditions, and vegetation are expected to affect the peatland carbon cycle. However, the combined effects of these changes on the carbon balance of Arctic and boreal peatlands remain uncertain. Understanding the photosynthetic activity of peatland vegetation and its temporal variability is therefore important for characterizing peatland carbon exchange and its response to changing environmental conditions.

Direct measurements of ecosystem carbon exchange using techniques such as eddy covariance provide valuable information on ecosystem carbon dynamics but remain spatially sparse, particularly in remote Arctic environments. Solar-induced chlorophyll fluorescence (SIF) is a weak radiation signal emitted by chlorophyll molecules in chloroplasts in the red and far-red spectral range (approximately 650–800 nm) following the absorption of solar radiation, providing an *in vivo* indicator of the

photosynthetic activity of vegetation. As SIF is closely linked to photosynthesis, it can provide information on vegetation carbon uptake (Porcar-Castell et al., 2021), and its relationship with gross primary productivity (GPP) has been widely studied. Previous studies have examined how the SIF-GPP relationship varies across vegetation types (Li et al., 2018, Li and Xiao, 2022), temporal scales (Pierrat et al., 2022), and environmental conditions, including water stress and climatic variability (Li and Xiao, 2022, Chen et al., 2021). Thus, remotely sensed SIF has emerged as a valuable proxy for GPP over the past decade (Yang et al., 2015, Pickering et al., 2022).

The coverage of SIF measurements remains limited and uneven across Arctic and boreal regions (Cheng, 2024), with relatively few ground-based canopy-scale SIF observations, particularly together with simultaneous measurements of ecosystem carbon exchange. Continuous ground-based measurements of the diurnal variation of the full SIF spectrum are also limited, especially at these high latitudes under unique illumination conditions, i.e., 24-hour daylight during summer time. Such measurements are important for improving our understanding of the relationship between SIF and ecosystem carbon dynamics and for supporting the interpretation and validation of satellite-based SIF observations at these latitudes. This is particularly relevant with the increasing availability of satellite SIF observations from instruments such as the European Space Agency's (ESA) TROPOspheric Monitoring Instrument (TROPOMI) and ESA's upcoming Fluorescence Explorer (FLEX) mission, which will provide spectrally resolved SIF observations at a spatial resolution of 300 m and with increased revisit frequency at high latitudes (Cogliati et al., 2015), providing new opportunities to study vegetation photosynthetic activity and its role in the Arctic carbon cycle.

To improve the understanding of the diurnal dynamics of SIF and its relationship with ecosystem carbon exchange in Arctic peatlands, this study presents continuous ground-based observations from two northern Finnish peatland sites collected during the 2023 and 2025 growing seasons. To our knowledge, this is the first study to present continuous 24-hour ground-based SIF observations from Arctic peatlands under natural illumination conditions. Spectrally resolved SIF was retrieved using the recently developed Bayesian SIFFI algorithm (Kukkurainen et al., 2025a, Kukkurainen et al., 2025b), allowing the diurnal variation of the full SIF spectrum to be examined. The objectives of this study are to characterize the diurnal and seasonal variability of spectrally resolved and integrated SIF, examine the performance of the SIFFI retrieval under different illumination conditions, and compare the diurnal dynamics of SIF with ecosystem CO₂ exchange.

2. Study Sites and Data

2.1 Study Sites: Lompolojänkki and Halssiaapa

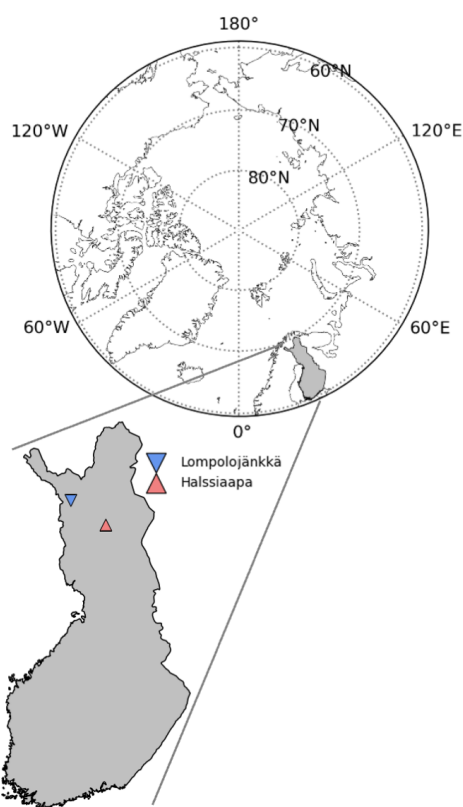


Figure 1. Locations of the two study sites, Lompolojänkki and Halssiaapa, in northern Finland. The upper panel shows the location of Finland within the Arctic region, while the lower panel presents the locations of the two sites in northern Finland.

Measurements for this study were conducted at two peatland sites in northern Finland, Lompolojänkki and Halssiaapa (Fig. 1). The sites represent boreal peatlands with contrasting vegetation structure and hydrological conditions (Fig. 2).

Lompolojänkki (67.9973°N, 24.2091°E; 269 meters above sea level) is a fen with a persistently high water table, resulting in near year-round saturation of the peat profile. Vegetation in wetter areas is dominated by sedges, and the moss layer is discontinuous (57% coverage, (Aurela et al., 2015)) due to the

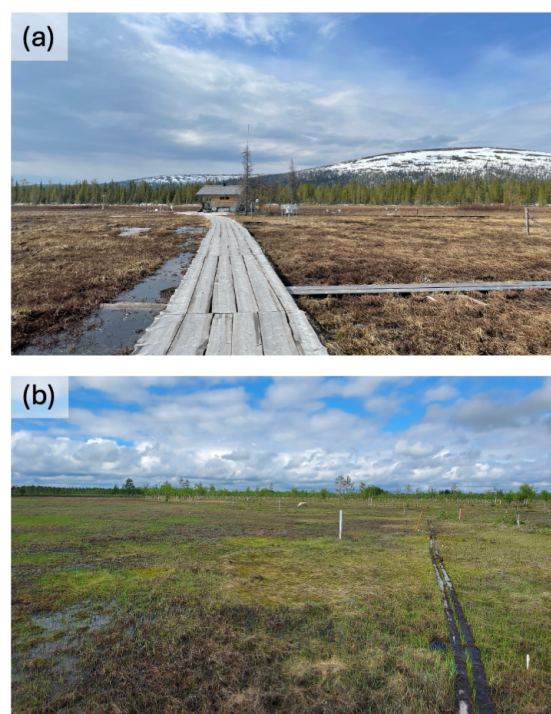


Figure 2. Photographs of the study sites showing their characteristic vegetation and hydrological conditions, (a) Halssiaapa in June 2025 and (b) Lompolojänkki in May 2023.

high-water level. The distance between the FloX instrument (see Sect. 2.2) and the target vegetation was less than 15 m.

Measurements at Lompolojänkki were collected from 16 May to 12 October 2023. For the present analysis, the dataset was restricted to June, July, and August. Data coverage during this period was affected by both missing data and the instrument's data-transmission schedule, so no 24-hour data was monitored for the Lompolojänkki site. Also, complete observations were unavailable during 11–14 August and 5–19 September. Until 22 July, data acquisition was interrupted nightly for approximately 3–4 h between 21:00 and 01:00 local time while the instrument transmitted the recorded data. Following a change in the instrument settings on 22 July, the transmission period was extended to 21:00–07:00 local time. To maintain consistent temporal coverage across the study period, observations between 21:00 and 01:00 were excluded from the entire dataset of Lompolojänkki. The extended transmission period after 22 July resulted in missing observations between 01:00 and 07:00 during the latter part of the measurement period.

Halssiaapa (67.3686°N, 26.6541°E; 180 meters above sea level) is also a fen, but it is characterized by a shallow string–lawn–flark pattern. Narrow (0.5–1 m) interconnected strings are dominated by shrubs (e.g., *Betula nana*), with scattered small birches (*Betula pubescens*) and pines (*Pinus sylvestris*). Flarks are dominated by wet brown mosses (notably *Sarmentypnum* spp.) and sedges, while lawns are covered by *Sphagnum* and forbs. The distance between the FloX instrument and the target vegetation was less than 3 m.

Measurements at Halssiaapa were collected from 3 June to 22 October 2025. The FloX acquisition settings were modified by JB Hyperspectral Devices to enable continuous 24-hour measurements, avoiding the nightly interruptions associated with data

transmission at Lompolojää. As for Lompolojää, only observations from June, July, and August were included in the present analysis to ensure comparable seasonal coverage between the two sites.

2.2 Measurements and Data Processing



Figure 3. The FloX measurement setup at the Halssiaapa study site. Two upward-facing optical fibers measure downwelling irradiance, while two downward-facing fibers measure upwelling radiance from the vegetation canopy. The spectrometers are located in the weatherproof enclosure near the base of the measurement pole.

At both sites, SIF measurements were performed using a fluorescence box (FloX; JB Hyperspectral Devices GmbH, Düsseldorf, Germany), which is an instrument specifically designed for passive measurements of SIF under natural illumination conditions. The FloX instrument includes two high spectral resolution spectrometers. The first covers the wavelength range of 650–800 nm at high spectral resolution and is optimized for retrieving SIF within the covered range and mainly on the O₂-A and O₂-B absorption bands. The second spectrometer covers the wavelength range of 400–950 nm at lower spectral resolution, enabling measurements of other vegetation remote sensing indices as well as the surface reflectance spectrum from the visible to the near-infrared region.

Both spectrometers are connected to two optical fibers: one equipped with a cosine receptor to measure the downwelling irradiance over a 180° field of view and another to measure the upwelling radiance from the vegetation canopy over a 23° field of view. The measurement setup at Halssiaapa is shown in Fig. 3; the optical fibers are mounted at the top of the measurement pole, with the downward-facing fibers directed at an angle towards the target vegetation. The fibers are connected to the spectrometers, which are located in a weatherproof enclosure near the base of the pole. At both study sites, the distance between the measurement head and the target vegetation was sufficiently short that atmospheric effects along the optical path were considered negligible. Therefore, no atmospheric correction was applied prior to the SIF retrievals (Sabater et al., 2018).

The FloX spectral measurements were processed by default us-

ing the FloX processing framework, which provides SIF retrievals based on spectral fitting (Meroni et al., 2010) and the improved Fraunhofer Line Discrimination (iFLD) method within the O₂-A and O₂-B absorption bands (Alonso et al., 2008). In addition, the measured spectra were processed separately using the SIFFI (Siffi Is For Fluorescence Inference) algorithm (Kukkurainen et al., 2025a, Kukkurainen et al., 2025b). In the present study, only the SIF retrievals obtained using SIFFI were used in the analyses. In previous studies, SIFFI has demonstrated high retrieval accuracy when applied to simulated datasets (Kukkurainen et al., 2025a). When applied to FloX data, SIFFI retrievals of SIF have shown close agreement when compared against SIF retrieved using the iFLD and spectral fitting method (Kukkurainen et al., 2025a).

SIFFI is a Bayesian retrieval algorithm that jointly estimates spectrally resolved SIF and surface reflectance from the measured spectra. Instead of relying strictly on deterministic point estimates or purely empirical models, SIFFI formulates the retrieval problem as a Bayesian inverse problem (Kaipio and Somersalo, 2005). This means that all unknown model parameters are treated as random variables. A major advantage of this Bayesian formulation is that it yields complete posterior probability distributions for the retrieved parameters, thus providing explicit estimates of their associated uncertainties.

A simple quality filter was applied to the SIFFI retrievals prior to the analysis to remove obvious outliers. A retrieved spectrum was retained if its minimum SIF value across the retrieved wavelength range was greater than $-0.1 \text{ mW m}^{-2} \text{ sr}^{-1} \text{ nm}^{-1}$ and its maximum SIF value was less than $2.0 \text{ mW m}^{-2} \text{ sr}^{-1} \text{ nm}^{-1}$. Duplicate observations with identical timestamps were also removed prior to the analysis.

In addition to the SIF measurements, eddy covariance CO₂ flux measurements were available for both sites and were used to compare the observed diurnal dynamics of SIF and ecosystem carbon exchange.

3. Results and Discussion

3.1 SIF and CO₂ Flux Time Series

Figure 4 shows the time series of SIFFI SIF integrated over the wavelength range 650–800 nm together with the corresponding eddy covariance CO₂ flux measured at Halssiaapa in July 2025. Negative CO₂ flux values indicate net CO₂ uptake from the atmosphere by the ecosystem, whereas positive values indicate net CO₂ release to the atmosphere.

The integrated SIF time series in Fig. 4 is limited to non-negative values, although some negative values were obtained after integrating the retrieved SIF spectra over 650–800 nm, with a minimum of $-7.04 \text{ mW m}^{-2} \text{ sr}^{-1}$. These negative integrated values occurred during Arctic summer nighttime with extremely low illumination conditions and were excluded from the figure and subsequent analysis. This filtering is separate from the quality filter applied to individual wavelengths of the retrieved SIF spectra described in Sect. 2.2. The occurrence and spectral characteristics of the negative SIFFI retrievals are discussed further in Sect. 3.2.

The time series illustrates similar temporal variation in SIF and ecosystem CO₂ exchange. For example, on 8 July, the maximum integrated SIF was relatively low, reaching approxi-

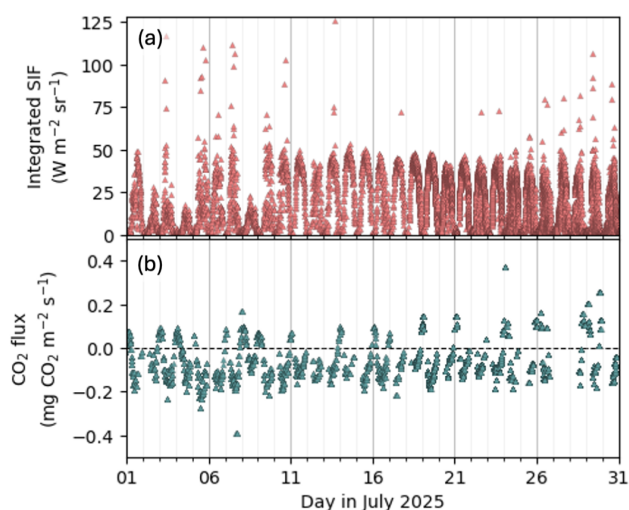


Figure 4. Time series of (a) SIFFI SIF integrated over the wavelength range 650–800 nm and (b) eddy covariance CO₂ flux at the Halssiaapa study site in July 2025.

ately $25 \text{ mW m}^{-2} \text{ sr}^{-1}$. On the same day, the CO₂ flux remained close to zero, indicating weak net CO₂ uptake compared with the surrounding days. The simultaneous decrease in SIF and net CO₂ uptake is consistent with reduced photosynthetic activity.

3.2 Mean Diurnal Cycles of Spectrally Resolved SIF

Figures 5 and 6 present the hourly mean spectrally resolved SIF spectra for each month at Lompolojää and Halssiaapa, respectively. Each spectrum represents the mean SIF spectrum for a given local hour, calculated from all available observations during the corresponding month. At both sites, the spectra show a clear diurnal cycle, with changes in both the magnitude and spectral shape of SIF throughout the day. The characteristic red and far-red fluorescence peaks are clearly distinguishable from morning to evening but become less pronounced during nighttime. In some extreme nighttime conditions, the low signal levels result in retrieved SIF spectra that are not physically plausible, with slightly negative values appearing in part of the red-edge region, suggesting that the observations are at the limit of detection.

At Lompolojää, the magnitude of the far-red fluorescence peak is relatively similar in July and August, whereas the red peak is slightly lower in August. At Halssiaapa, the overall SIF magnitude is generally lower than at Lompolojää throughout the three summer months. These differences are likely related to the contrasting vegetation structure and hydrological conditions of the two sites. As described in Sect. 2.1, the sites differ in their vegetation composition and hydrological conditions, particularly in the relative contributions of sedges, shrubs, and mosses and in their water table characteristics. Previous studies have also shown that SIF in northern peatlands is sensitive to hydrological conditions, including changes in water table depth (Valkenborg et al., 2023), suggesting that the contrasting hydrological conditions at Lompolojää and Halssiaapa may contribute to the observed differences in SIF magnitude. Both datasets were collected during relatively warm summers in Northern Finland. In 2023, summer mean temperatures in northern Lapland were more than 1°C above the 1991–2020 climatological average, while in 2025 temperatures across Lap-

land were 0.8–1.2°C above average (Finnish Meteorological Institute, 2024, Finnish Meteorological Institute, 2026). Thus, although the measurements were conducted in different years, both datasets represent similarly warm summer conditions relative to the climatological average, suggesting that differences in summer temperature alone are unlikely to explain the observed differences in SIF magnitude.

The retrieved spectra also show some limitations under conditions of low illumination. During nighttime and, to a lesser extent, during morning and evening twilight, some of the spectra contain physically unrealistic negative SIF values. These negative values are most clearly observed between the red and far-red fluorescence peaks, approximately at 700–725 nm, where the retrieved SIF occasionally falls below zero. When the spectrum is integrated over 650–800 nm, the negative values at individual wavelengths accumulate and can result in negative integrated SIF values, as observed in the time series in Sect. 3.1. The negative values under low illumination may suggest a limit in terms of minimum incoming radiance and SIF signal in which the current implementation of the SIFFI algorithm is able to obtain reliable SIF estimates. These very low illumination conditions during nighttime and twilight in the northern Finnish summer remain challenging for any retrieval strategy and could be considered in the further development of SIFFI.

Despite these limitations at low illumination levels, the SIFFI retrievals reproduce the characteristic spectral shape of SIF during illuminated hours, with clearly distinguishable red and far-red fluorescence peaks and small changes in their relative magnitudes throughout the day. This indicates that SIFFI can capture both the magnitude and spectral variation of SIF under natural field conditions.

The interpretation of the nighttime spectra at Lompolojää in July and August is further complicated by gaps in nighttime observations caused by the FloX data transmission schedule described in Sect. 2.2. However, as the nighttime spectra are also affected by the limitations of the current SIFFI retrieval under conditions of low illumination, the missing nighttime observations are not expected to substantially affect the overall interpretation of the diurnal patterns. Shorter data gaps are also present elsewhere in both datasets, but their influence on the monthly mean spectra is expected to be minor because each hourly mean is calculated from a relatively large number of observations.

3.3 Mean Monthly Diurnal Cycles of SIF and CO₂ Flux

Figures 7 and 8 show the monthly mean diurnal cycles of spectrally integrated SIF and eddy covariance CO₂ flux at Lompolojää and Halssiaapa, respectively. At both sites, SIF increases during the daytime simultaneously with the increase of net CO₂ uptake and decreases towards the evening as the CO₂ flux returns towards net emission. The magnitude and timing of these changes, however, differ between months and between the two sites.

The monthly differences in SIF are consistent with those observed in the spectrally resolved SIF in Sect. 3.2. At Lompolojää, the SIF diurnal cycles in July and August are relatively similar in magnitude, whereas a clearer difference between these months is observed in the CO₂ flux. Net CO₂ uptake is stronger in July than in August, despite the relatively similar SIF magnitude. At Halssiaapa, in contrast, the maximum net

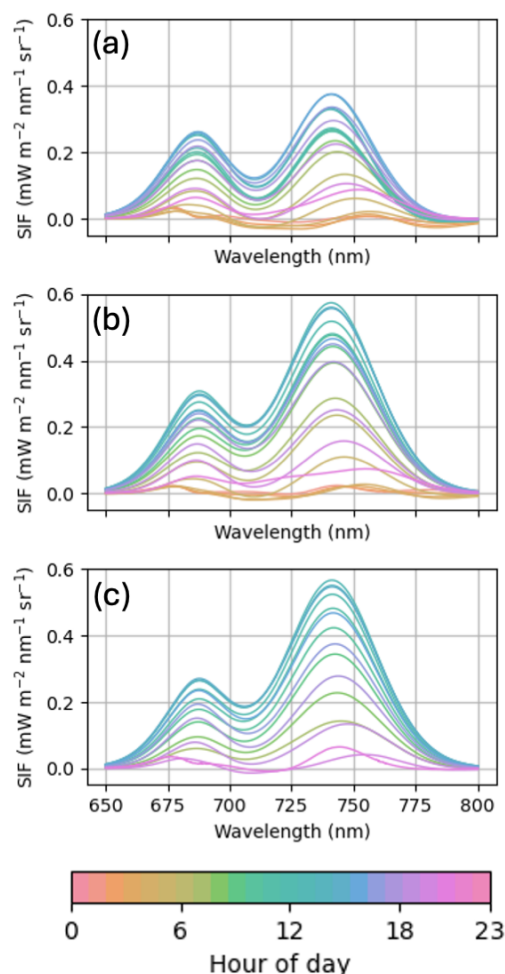


Figure 5. Hourly mean spectrally resolved SIF spectra at the Lompolojankkä site for (a) June, (b) July, and (c) August 2023. Each curve represents the mean of all available SIF spectra within a given local hour during the corresponding month. Colours indicate the hour.

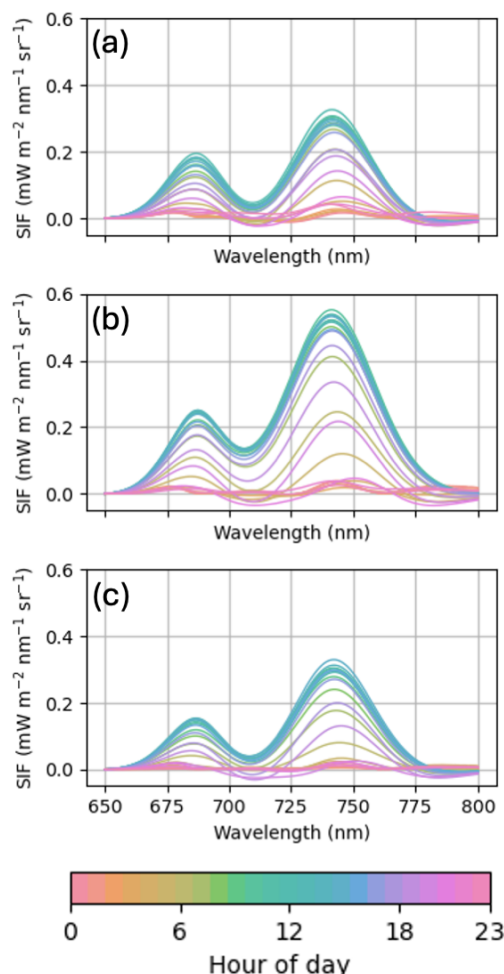


Figure 6. Hourly mean spectrally resolved SIF spectra at the Halssiaapa site for (a) June, (b) July, and (c) August 2025. Each curve represents the mean of all available SIF spectra within a given local hour during the corresponding month. Colours indicate the hour.

CO₂ uptake varies relatively little between June, July, and August.

At both sites, the period of net CO₂ uptake becomes shorter towards the end of the summer. This is visible as a later transition from net CO₂ emission to uptake in the morning and an earlier transition back to net emission in the evening. The shortening of the uptake period coincides with the seasonal decrease in day length from June to August. However, the SIF magnitude at the transition between net CO₂ emission and uptake is not constant, but differs between months and between the two sites.

The differences between the SIF and CO₂ flux diurnal cycles are expected because the two measurements represent different aspects of ecosystem carbon dynamics. SIF is associated with vegetation photosynthetic activity, whereas the measured CO₂ flux represents net ecosystem CO₂ exchange and therefore reflects the balance between photosynthetic CO₂ uptake and ecosystem respiration. Consequently, similar SIF levels do not necessarily correspond to similar net CO₂ fluxes. This may partly explain both the difference between the July and August CO₂ flux cycles at Lompolojankkä despite their relatively similar SIF magnitude, and the variation in SIF at the transition between net CO₂ emission and uptake.

4. Conclusions

To the best of the authors' knowledge, this work provides the first continuous 24-hour record of SIF measured under natural boreal peatland conditions. The SIFFI retrievals captured the characteristic spectral shape and diurnal variation of SIF, including distinct red and far-red fluorescence peaks during the illuminated hours. Under extreme low-illumination conditions, the retrieval occasionally produced physically unrealistic negative SIF values. Although these negative values may fall within the retrieval uncertainty of the SIFFI method, further development of the algorithm would be beneficial to improve its performance under nighttime and twilight conditions.

A preliminary comparison of spectrally integrated SIF and CO₂ fluxes showed that higher SIF values generally coincided with periods of net CO₂ uptake as expected. However, the strength of this relationship varied across sites and months, reflecting the combined influence of photosynthetic activity and ecosystem respiration on net ecosystem CO₂ exchange. Overall, these findings highlight the potential of continuous, spectrally resolved SIF measurements to support investigations of photosynthetic activity and diurnal carbon dynamics in boreal peatlands.

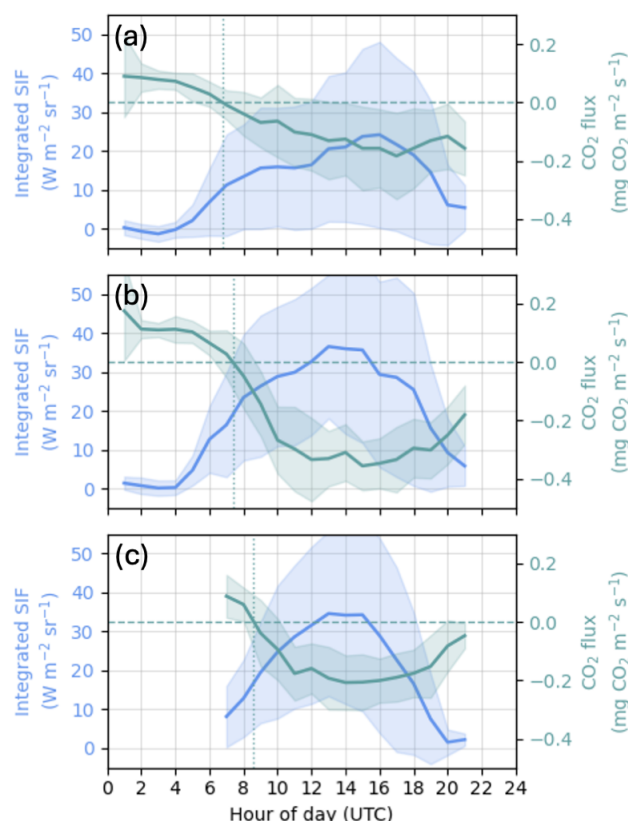


Figure 7. Mean diurnal cycles of spectrally integrated SIF and eddy covariance CO_2 flux at the Lompolojankkä site during (a) June, (b) July, and (c) August 2023. Solid lines show the monthly mean values and shaded areas indicate ± 1 standard deviation. The horizontal dashed line denotes zero CO_2 flux, and the vertical dotted line(s) mark the transition(s) between net CO_2 emission and net CO_2 uptake.

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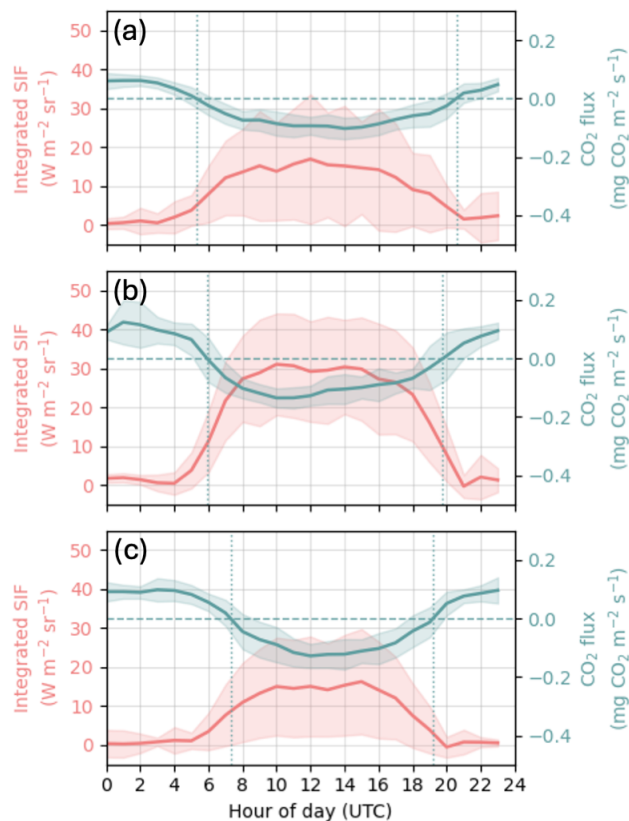


Figure 8. Mean diurnal cycles of spectrally integrated SIF and eddy covariance CO_2 flux at the Halssiaapa site during (a) June, (b) July, and (c) August 2025. Solid lines show the monthly mean values and shaded areas indicate ± 1 standard deviation. The horizontal dashed line denotes zero CO_2 flux, and the vertical dotted line(s) mark the transition(s) between net CO_2 emission and net CO_2 uptake.

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