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THE CARBON DIOXIDE FLUXES AT THE OPEN-TOP CHAMBERS EXPERIMENT ON THE OMBROTROPHIC BOG (MUKHRINO FIELD STATION)

Zarov E.A.[1*], Jacotot A.[2], Kulik A.A.[1], Gogo S.[2], Lapshina E.D.[1], Dyukarev E.A.[1, 3]

[1] *Yugra State University, Khanty-Mansiysk, Russian Federation*
[2] *Laboratoire ECOBIO, Physicien adjoint, Observatoire des Sciences de l'Univers de Rennes, Rennes, France*
[3] *Institute of Monitoring of Climatic and Ecological Systems, SB RAS, Tomsk, Russian Federation*

* zarov.evgen@yandex.ru

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Abstract. The continuous measurement of CO_2 fluxes at the open-top chamber experiment in the ombrotrophic peatland (located in the middle taiga zone, West Siberia, Russia) has been provided during the warm season of 2022 (beginning of June to beginning of October). The R_{eco}, NEE and GPP were calculated for this period; abiotic factors related to CO_2 emissions, such as PAR, air temperature, water table level and precipitation, were also measured. The monthly average values showed a negative NEE of -9.89 C g m^{-2} month^{-1} in July, a negative GPP of -34.19 C g m^{-2} month^{-1} in July, and a positive values R_{eco} of 41.68 C g m^{-2} month^{-1} in August. In 2022, the studied peatland hollows were only a carbon stock in July, while in the remaining months they were a source of CO_2, which could be caused by small precipitation amount. The monthly average diurnal variations of CO_2 fluxes showed similar behaviour for both the OTC plot and control plot fluxes, which may be explained by the similarity in vegetation cover.

Аннотация. На территории верхового болота, расположенного в среднетаёжной зоне Западной Сибири, на протяжении полевого сезона (с июня по октябрь) 2022 года, были измерены потоки CO_2. Измерения проводились на участке мочажины, подверженной влиянию повышения приземной температуры воздуха за счёт установки камер с открытым верхом (OTC-эксперимент). Для исследуемого периода были рассчитаны значения R_{eco}, NEE и GPP; дополнительно измерялись абиотические факторы, такие как ФАР, температура воздуха, уровень грунтовых вод и осадки. Средние показатели за месяц продемонстрировали отрицательное значение NEE -9,89 C г м$^{-2}$ месяц$^{-1}$ в июле, отрицательное значение GPP -34,19 C г м $^{-2}$ мес$^{-1}$ в июле и положительное значение R_{eco} 41,68 C г м$^{-2}$ мес$^{-1}$ в августе. В 2022 году значение NEE для мочажин было отрицательным (поглощение CO_2) только в июле, а в остальные месяцы значение NEE было положительным (выделение CO_2), что может быть вызвано малым количеством осадков. Среднемесячная суточная динамика потоков CO_2 продемонстрировала сходное поведение, как для участка с OTC, так и для контрольных участков, что можно объяснить сходством растительного покрова.

Key words: carbon dioxide, net ecosystem exchange, ecosystem respiration automatic chambers, peatland, open-top chamber, West Siberia, seasonal dynamic

Ключевые слова: углекислый газ, чистый экосистемный обмен, экосистемное дыхание, автоматические камеры, болото, камера с открытым верхом, Западная Сибирь, сезонная динамика

Abbreviations: *C – carbon, OM – organic matter, WTL – water table level, NEE – net ecosystem exchange, R_{eco} - ecosystem respiration, GPP – gross primary production, OTC – open top chambers.*

INTRODUCTION

Anthropogenic emissions of greenhouse gases to the atmosphere have increased significantly since preindustrial times, reaching the highest levels uin the last 66 million years (Zeebe et al., 2016). These carbon (C) emissions are causing a strong warming effect (Cook et al., 2016), with global air temperatures predicted to rise by 0.3 to 4.8°C by the end of century, depending on prediction models. There is now an urgent need to evaluate the consequences of these increased temperatures on the ability of natural ecosystems to absorb and store carbon, in order to implement appropriate climate change mitigation programs such as conservation and restoration strategies for ecosystems.

Among the various ecosystems, peatlands are considered as one of the largest stocks of atmospheric carbon. They represent a highly powerful carbon pool, with more than 30% of earth's carbon stored in their soils, despite only 3% of land surface (Harenda et al., 2018). This distinctive characteristic is mainly due to long term, slower organic matter (OM) decomposition than primary productivity. The exceptionally low OM decomposition is a result of a combination of factors such as the waterlogged soils that are mostly anoxic, low pH, and low nutrient availability (e.g. Loisel et al., 2014; Treat et al., 2019). As a result, CO_2 emissions from peatlands are usually considered low, with the ecosystem acting as a carbon sink. However, current global changes have the potential to severely impact the carbon dynamic of peatlands. As temperature increase, photosynthetic rates tend to plateau, while ecosystem respiration could still increase exponentially (Golovatskaya and Dyukarev, 2011). This combination, depending on temperature increase, vegetation, and soil responses, could transform the ecosystem from a sink of C into a source. In addition, an increase in surface temperature will increase water evaporation, lowering the soil water table level (WTL), oxygenating the soil, and increasing OM decomposition and gas molecular diffusion to the surface, leading to higher gas fluxes and lower carbon accumulation. Recent research estimates that peatlands could lose 30 to 203 GtC (gigatons of carbon) with only 1°C increase (Crowther et al., 2016).

Boreal peatlands make up 80% of the world's peatlands and contain a significant portion of their carbon pool, with an estimated stock of 500±10 GtC (Yu, 2012). Western Siberia, in particular, is home to large areas of pristine peatlands, making it an ideal location to study the impact of global changes on the biogeochemical functioning of peatlands worldwide.

In this paper, we aim to use the results of 8 years of artificial warming experiment to evaluate the long-term effects of warming on the carbon cycle of the mire. Our objective is *to determine how a simulated temperature increase affects CO_2 fluxes (both photosynthesis and respiration) in a sub-boreal peatland, by making high temporal frequency measurements of the CO_2 exchange at the soil-air interface.*

We aim to understand how peatlands will respond to future elevated temperatures, as this is crucial for predicting their role in climate change mitigation. We will accomplish this by conducting experiments at a unique experimental station in a highly relevant ecosystem. Long-term warming experiments and data on Siberian peatlands are currently lacking, making the results of this study particularly impactful.

Furthermore, data from Siberian peatlands is scarce, despite Siberia containing the largest peat-accumulating system in the world. The datasets obtained during this study will be valuable to the scientific community, particularly to global modelers who currently lack experimental data from this important region. This experiment will help to fill a long-standing spatial gap of our understanding of the linkages between plant, microbial and soil processes and how they respond to and feedback to climate warming.

MATERIALS AND METHODS

Mukhrino location map and measurement points

The Mukhrino field station is located in the middle taiga zone of western Siberia (55-65 N latitude, the Russian Federation). The station occupies the left terrace of the Irtysh River, located approximately 20 km west of Khanty-Mansiysk city and 20 km south of the confluence point of the Irtysh and Ob' rivers.

Most of the measurements are carry out at the Mukhrino peatland, a vast pristine ombrotrophic (rain-fed) bog. The most dominant ecosystems are ridge-hollow complexes and ryams. The vegetation consists of a mix of *Carex limosa*, *Eriophorum vaginatum*, and *Scheuchzeria palustris* covering a *Sphagnum* moss mat in hollows, which may become submerged after a snow melting period. Ridges (30-40 cm in height, 10-100 m in length) are elongated across water flow, dominated by a mix of *Pinus sylvestris*, dwarf-shrubs (*Chamaedaphne calyculata*, *Ledum palustre*, *Andromeda polifolia*) and *Sphagnum fuscum*. Ryams are dense treed by *Pinus sylvestris* together with the dwarf-shrubs like to the ridge vegetation diversity. The peatland was initiated ~12 kyr ago as a minerotrophic fen with dominance of brown mosses, sedges, and wood. The average thickness of the peat deposits is ~3.3 m, mostly composed of oligotrophic peat (dominant remains are *Sphagnum* mosses and shrubs) (Zarov et al., 2022).

The environmental monitoring system is organized at the station. The main measured properties are the air pressure, radiation balance, precipitation, WTL, air and soil temperatures, greenhouse gas fluxes (methane and carbon dioxide), as well as geobotanical surveys (vegetation and fungus) and hydrochemistry (ions and dissolved organic carbon). The data have been available since 2010 (Dyukarev et al., 2021).

Abiotic factors measurements

During the study period, various environmental features were measured. The air temperature was measured using a Rotronic AC1000 sensor, wich was protected by a naturally ventilated radiation shield. The photosynthetic active radiation (PAR) was measured using a LI-COR LI-190R sensor. These sensors were connected to Campbell Scientific data loggers CR10X with AM16/32A multiplexers to collect data.

A water level logger (HOBO U20L-02, with an accuracy of ±0.3% full scale and a measurement frequency of 60 minutes) was installed in perforated groundwater observation tubes (5 cm diameter) at a depth of approximately 2 m. The tube was fixed in mineral soil (at a depth of 350 cm below the peat surface) to prevent vertical movement caussed by peat volume expansion or compression. For barometric compensation, the air pressure and temperature were recorded using a pressure sensor (Baro-diver, with an accuracy of ±5 mm of water and a measurement frequency of 30 minutes) placed in the centre of the mire 2 m above the surface. Barometric compensation was performed using the R-language (version 4.2.2) with the “dplyr” library.

The rain precipitation was monitored using a tipping-bucket rain gauge (Hobo RG3-M, resolution 0.2 mm) located in the hollow at the 30 cm height from the peatland surface.

Experiment design

The research is based on a collaboration with the University of Rennes within the INTERACT network and is closely aligned with the research effort previously initiated at the Mukhrino station by the CliMireSiber project (INTERACT 2012; project leader: F. Laggoun-Défarge, CNRS, France). The main objective of CliMireSiber was to equip and prepare the site for further experiments on the effects of temperature on the carbon cycle of the peatland. To achieve this, 30 open-top chambers (OTCs; Figure 1; Aronson and McNulty, 2009) were installed on the peatland at the Mukhrino Field Station (MFS) to simulate global warming. The open-top chamber (OTC) is a passive warming device widely used to experimentally simulate a warm year at a site (Henry et al., 2022). The effect of WTL was considered as the OTCs were installed in two areas differing in WTL and vegetation. In 2020, after 8 years of installation, measuring CO_2 fluxes provides a unique opportunity to identify a long-term effect of increasing temperature on the carbon cycle of the mire.

Figure 1: Picture of the OTCs implemented in the Mukhrino Field Station in 2013 (S. Gogo, 2013).

Measurement of CO_2 fluxes

CO_2 fluxes between the ecosystem and the atmosphere were evaluated with the closed dynamic chamber method, a widespread and powerful technic of measurements. In research, we used 8 automatic chambers (LI-COR LI-104C) connected to a CO_2/H_2O analyser (LI-COR LI-8100A) through a multiplexer (LI-COR LI-8150A) that allows to allocate the flow from the active chamber to the analyser. This system is part of the PIVOTS-PESAt platform (https://plateformes-pivots.eu/pesat/?lang=en) based at the Institut des Sciences de la Terre d’Orléans (ISTO).

Specifically, we used 4 opaque and 4 transparent chambers. Opaque chambers enable to measure the ecosystem respiration R_{eco} while transparent chambers allow to measure the net ecosystem exchange NEE. Gross primary production GPP (i.e. the carbon fixed by the vegetation from the atmosphere) has been calculated as follow: GPP = NEE - R_{eco}. Gas accumulation within chamber headspace lasts 2 minutes every 30 minutes for each chamber. Incubation of 2 minutes was enough to have representative fluxes, without causing any significant disturbance (e.g. temperature or humidity increase) that may impact the flux.

Recorded data was regularly collected, stored, and analysed. Fluxes calculations was done through the specific software Li-8100 (LI-COR), and then was related to treatments and to environmental variables.

The instrument was deployed from May to October 2022, which allowed for the monitoring of five months of net CO_2 exchange and the coverage of the complete vegetation season. The chambers were distributed as follows: two opaque chambers in the control plots, two opaque chambers in the warm (OTC) plots, two transparent chambers in the control plots and two transparent chambers in the warm (OTC) plots. The data are available through the zenodo.org portal[1].

During the installation in early spring, five chambers were damaged by snow-melt water and stopped working for approximately 30 days. Thanks to the efforts of the engineers at Yugra University. three chambers were restored. However, two chambers (one opaque and one transparent chamber) were broken and not installed for further measurements. Thus, three transparent chambers (two in the OTC plot and one in the control plot) and three opaque chambers (one in the OTC plot and two in the control plot) were installed (Figure 2). A measurement gap occurred from 14th July to 22d July due to a power cut.

Figure 2. Location of the measurement plots. The white fill – clear chambers, the black fill – opaque chambers, the blue stroke – OTC sites, the green stroke – control sites.

RESULTS & DISCUSSION

The seasonal air temperature increased from the beginning of May and reached its maximum in the middle of July (Figure 3). Positive temperatures were observed throughout the entire preriod, with short-term frosts occurring in May and at the end of September. The highest monthly average air temperature was found in July (18.2°C), while the lowest monthly air temperature, which featured a dramatic drop, was found in September (7.1°C). The end of May was extremely warm with a daily average air temperature of 24°C, before decreasing to 7 °C.

The PAR followed a similar trend to the air temperature, increasing untill the middle of July before gradually decreasing towards the end of the season (Figure 3). The highest daily PAR values were found in June 17th (544.1 μmol m^{-2} s^{-1}) and July 8th (511.5 μmol m^{-2} s^{-1}), with a sharp drop to the smallest value found in September 9th (46.2 μmol m^{-2} s^{-1}). Several local minimum values were found in May and June, which coincided with drops in air temperature.

1 10.5281/zenodo.7544523

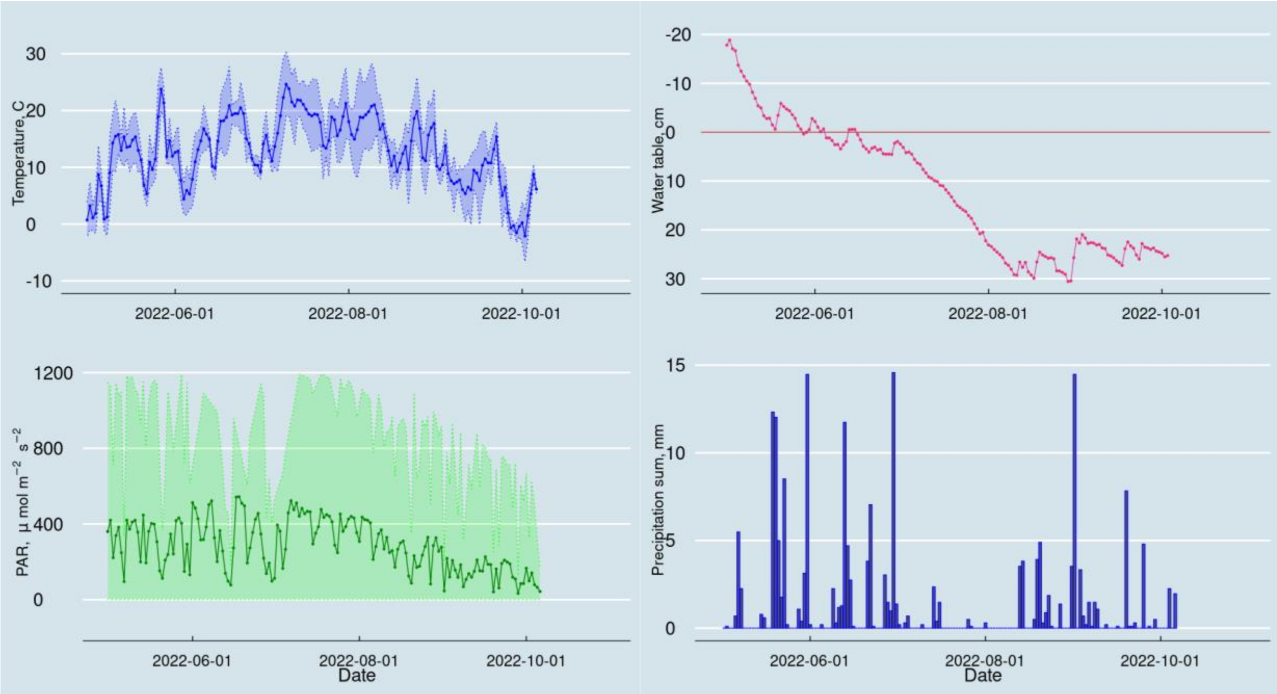

Figure 3. Seasonal variation of air temperature, photosynthetically active radiation (PAR), WTL (brown line is the surface level, positive values mean water level below the surface) and the sum of precipitation. The lines show the daily average values, shades show the minimum and maximum diurnal variation of the feature.

The WTL in the peatland increased in May due to snowmelt and gradually decreased until the end of the season. Small local increase in WTL occurred after rainfall events. The WTL remained above the peatland surface for May and the first half of June, before dropping below the surface. The WTL increased again at the end of August due to intense rain events and a low evapotranspiration rate (Figure 3).

Precipitation events were not evenly distributed throughout the season (Figure 3). Snowmelt caused the highest rise in WTL and sustained the peatland until the mid-May. Most of the rainfall occured during the May-June and August-September period With a total seasonal (May-first decade of October) precipitation amount of 193.7 mm which significantly less the long-term average value of 365 mm.

The seasonal diurnal variation of CO_2 fluxes for different chambers is shown in Figure 4. The daily average NEE rate (transparent chambers) changed from slightly positive (0 - 0.9 μmol m^{-2} s^{-1}) values (carbon release) in the beginning of May-June to slightly negative (-0.12 - -0.2 μmol m^{-2} s^{-1}) values (carbon uptake) on June 15th and reached its the negative extreme (-2.0 - -2.7 μmol m^{-2} s^{-1}) values (carbon uptake) on July 12th (Figure 5a). The NEE turned back to positive values on August 4th and remained positive until to the end of September when measurements were halted.

The monthly average values of GPP and NEE are shown in Figure 5b. The negative extreme values (carbon uptake) for NEE (-9.88 g m^{-2} $month^{-1}$) and GPP (-34.19 g m^{-2} $month^{-1}$) were found in July (the warmest month with the highest PAR). Other months had positive values of NEE (carbon release) and negative values of GPP.

Plot 1 and plot 2 exposed in the OTC showed higher variations in fluxes (both negative and positive) when compared to control plot 5 which had a narrower flux variation (Figure 4). The highest flux variation was found in August for all transparent chambers.

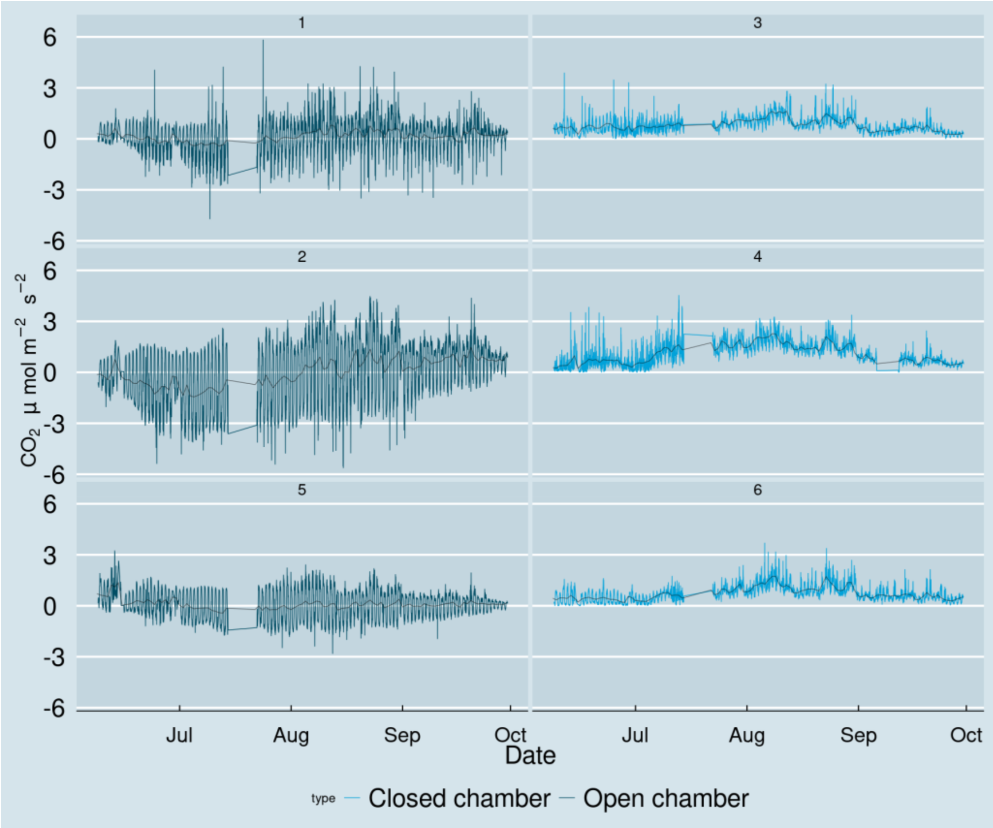

Figure 4. Seasonal variation of the CO_2 fluxes over the season 2022

The R_{eco} rate increased from the beginning of June (approximately 300-600 C mg m^{-2} day^{-1}) to the first decade of August (approximately 1300-1800 C mg m^{-2} day^{-1}) and then decreased until the end of September when measurements were stopped (Figure 5a). The highest R_{eco} value was found twice on 9th August (1827.8 C mg m^{-2} day^{-1}) and 23rd August (1827.2 C mg m^{-2} day^{-1}). The chamber located in the OTC (plot 3) showed the highest flux values variation and number of outlayers in June and July, while the control chamber (plot 4 and plot 6) showed smaller flux values variation in June and July, and higher variation in August.

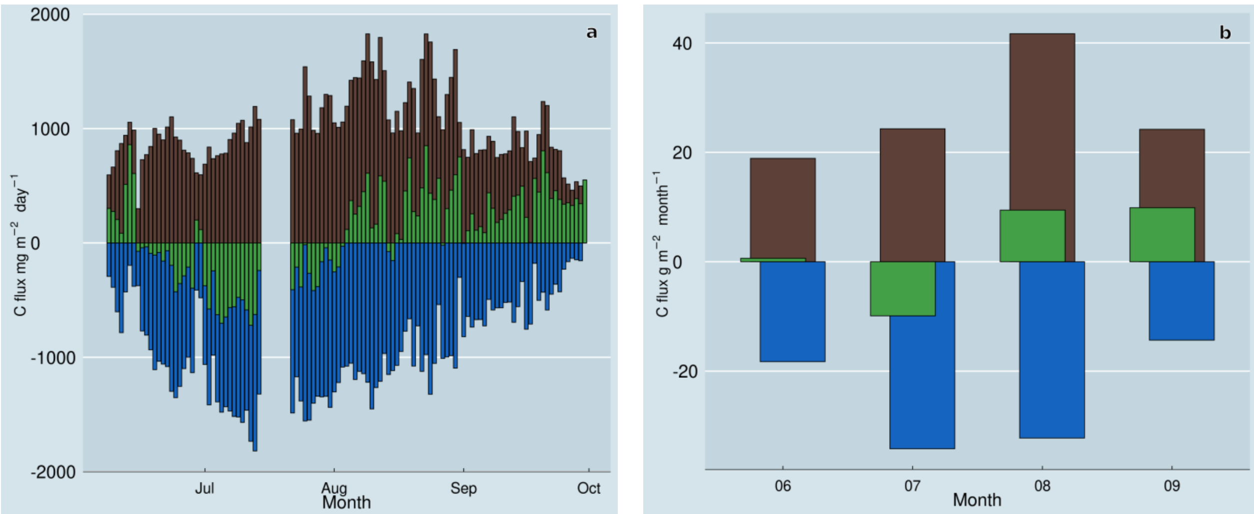

Figure 5. Daily (a) and monthly (b) sums of the NEE (green bars), GPP (blue bars) and ER (brown bars) calculated for all chambers[2]

The diurnal flux patterns of the transparent chambers during the summer did not vary significantly (Figure 6a). In September, the range of these values was smaller due to a sharp decrease in air temperature. The NEE turned to negative values at 5:00-6:00 and turned to positive values at 16:00-17:00. The highest

2 The values for July, where the gap appears, were calculated as mean values multiplied by 30 days

values (~2.4 μmol m^{-2} s^{-1}) for all transparent chambers were found in August during the time period 20:00-04:00, while the negative extreme values (~-3 μmol m^{-2} s^{-1}) for all transparent chambers were found in July at noon. Unexpectedly, the shapes of the two chambers with OTC were not similar, but the curve of the control chamber (plot 5) was close to the OTC chamber (plot 1), which could be explained by the similarity in vegetation cover.

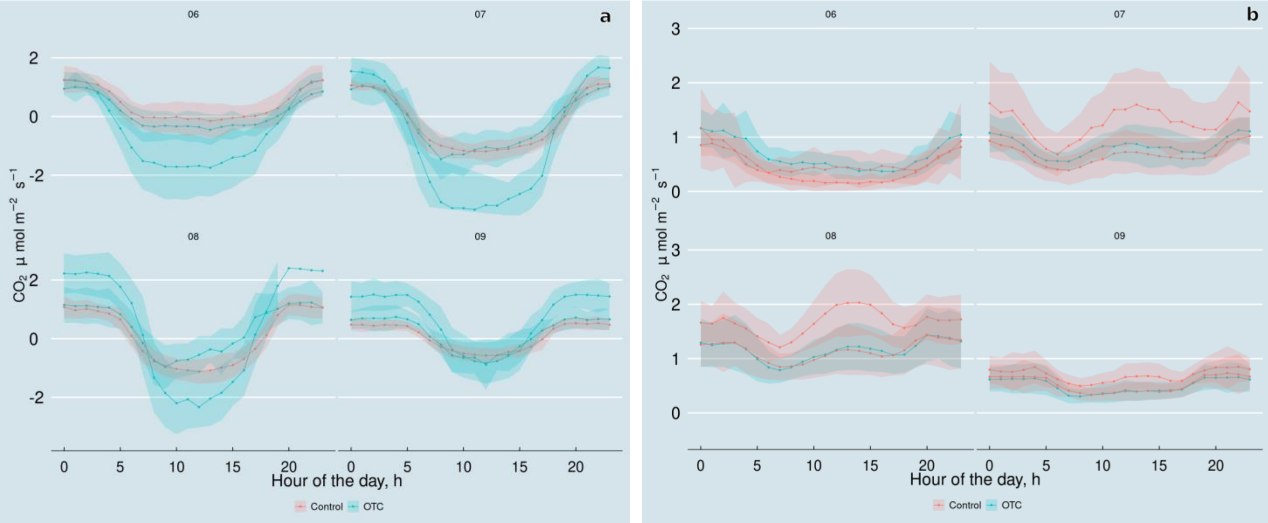

Figure 6. Monthly averaged diurnal variations of CO_2 fluxes for the different chambers (a – the transparent chambers, b – opaque chambers) in June-September (the shades are the minimal and maximal values). May data are not shown in figure.

The diurnal flux patterns of the opaque chambers for the July-September period were similar (Figure 6b), with the exception of May, which showed a different trend but remained withung the same range of values. The nightly highest values in the opaque chambers were found during the 21:00-3:00 (~1.3-1.7 μmol m^{-2} s^{-1} in June-August and ~0.7 μmol m^{-2} s^{-1} in September). A local daily increase in values was observed during the 11:00-15:00 time period in July-September, with a significant (higher than night-time flux) increase of 1.5-1.6 μmol m^{-2} s^{-1} in July-August. The opaque chambers showed a similar pattern to the transparent chambers, with control plot fluxes not being similar to each other, but one control chamber flux (plot 6) being close to the OTC chamber flux (plot 3). This may be explained by the similarity in vegetation cover.

CONCLUSION

The initial results of the CO_2 fluxe measurements taken at the OTC experiment in the ombrotrophic peatland (Mukhrino field station) have been analysed. The high temporal frequency measurements of CO_2 exchange at the soil-air interface have been implicated from May to October 2022. These data allowed to estimate the seasonal variation of the CO_2 fluxes for both control plots (without any manipulation) and OTC plots (with temperature increase).From June to the beginning of October, NEE, R_{eco}, and GPP have been calculated. The monthly average values showed a negative NEE (carbon uptake) of -9.89 C g m^{-2} $month^{-1}$ in July, a negative GPP of -34.19 C g m^{-2} $month^{-1}$ in July, and positive R_{eco} (carbon release) of 41.68 C g m^{-2} $month^{-1}$ in August. In 2022, the studied peatland hollows were only a carbon stock in July, while the remaining months they were a source of CO_2. Possibly, this caused by the low precipitation rate in the May-September of 2022.

The monthly average diurnal variations of CO_2 fluxes indicated that the main differences between the fluxes for the various plots were caused by the vegetation cover rather than the air temperature manipulation (OTC effect). However, further investigation is needed to confirm this hypothesis.

The next step in the research is to determine the statistically significant differences between the OTC and control plots to reveal the role of air temperature warming on the peatland ecosystems. Additionally, the role of abiotic factors such as PAR, WTL, precipitation and vegetation cover must be considered and evaluated as the main factors controlling CO_2 emissions.

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