



## THE IMPACT OF WILDFIRE ON THE VARIABILITY OF NET CO<sub>2</sub> FLUX AND ITS COMPONENTS IN WETLANDS (A CASE STUDY ON BIEBRZA NATIONAL PARK, POLAND)

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**Abstract.** Vertical carbon dioxide (CO<sub>2</sub>) exchange measurements in Kopytkowo (Middle Basin of the Biebrza National Park, NE Poland) have been conducted since 2012. Continuous measurements have enabled us to characterise the temporal variability of CO<sub>2</sub> fluxes and the factors that determine it. These include, above all, air and ground temperature, groundwater level, liquid and solid precipitation, and the length of snow cover. Because these factors show long-term variability, the CO<sub>2</sub> exchange rates also change from year to year. Short-term processes (both natural and anthropogenic) are also occasionally observed in wetland ecosystems, but the changes they cause are long-lasting. One such process (alongside, for example, mowing of low vegetation or intense hailfall) is wildfire. On April 20–25, 2020, a large fire in the Middle Basin of the Biebrza National Park burned 5,526 ha of marshes, which is about 9.5% of the park's area. The aim of this study is to analyse the impact of the fire on the temporal variability of net CO<sub>2</sub> exchange in the wetland area. Initially, due to the complete burning of vegetation, a significant decrease in CO<sub>2</sub> exchange intensity was observed, which, with vegetation regrowth in June and July 2020, was clearly higher than in 2017–2019. The study also analysed the impact that vegetation burning in wetlands has on the components of the net CO<sub>2</sub> flux – respiration and gross primary production.

**Key words:** Carbon dioxide exchange, wetland, CO<sub>2</sub> flux, biomass burning, NE Poland

### Introduction

Wetlands, despite occupying a small percentage of land area, play a significant role in the environment (Rydin, Jeglum 2006; Lund *et al.* 2010; Aubinet *et al.* 2012; Čížková *et al.* 2013; Olson *et al.* 2013; Fortuniak *et al.* 2021). From a climatological point of view, their most important features are their capacity for long-term storage of water

and, above all, carbon – as peat formed during long-term processes of organic matter limited decomposition in substrates with high water content (Okruszko 1990; Okruszko, Byczkowski 1996; Rydin, Jeglum 2006; Lindroth *et al.* 2007; Lund *et al.* 2010; Grygoruk *et al.* 2011; Hatala *et al.* 2012). Long-term studies of carbon dioxide (CO<sub>2</sub>) exchange between the substrate and the atmosphere conducted in wetlands in various climate zones

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have confirmed that, when the substrate is highly moist, plants intensively uptake CO<sub>2</sub> from the air (Lindroth *et al.* 2007; Lund *et al.* 2010; Hatala *et al.* 2012; McVeigh *et al.* 2014; Fortuniak *et al.* 2017, 2021). Wetlands therefore also act as long-term reservoirs for carbon, which, under normal conditions, block excessive natural CO<sub>2</sub> emissions into the atmosphere. Measurements of CO<sub>2</sub> fluxes and wetland biodiversity have shown a close relationship between these factors and weather variability in wetlands. Air and soil temperature, groundwater level and, consequently, soil moisture are of key importance here (Lund *et al.* 2010; Kettridge *et al.* 2015; Schiau *et al.* 2016; Olefeldt *et al.* 2017; Baldocchi 2018; Evans *et al.* 2021; Fortuniak *et al.* 2021, 2026; Rakovec *et al.* 2022; McDonald *et al.* 2023; Satriawan *et al.* 2023). The climate changes observed have led to increased air temperatures, which in the Biebrza National Park (Biebrza NP) manifest primarily in milder winters, with snow cover of shorter duration and significantly reduced thickness (Siedlecki *et al.* 2016; Fortuniak *et al.* 2017, 2021, 2026; Pawlak *et al.* 2025). As a result, the spring thaw is very short, the groundwater level drops, and summer rainfall does not replenish the losses, leading to drought. In such situations, a decrease in CO<sub>2</sub> uptake intensity has been recorded in the Biebrza NP area, and, in extreme cases, the area even shifting from a CO<sub>2</sub> sink to a CO<sub>2</sub> source for the atmosphere (Fortuniak *et al.* 2017, 2021, 2026). This phenomenon may also be anthropogenic, caused by drainage works intended to lower the water level in the marsh. Such works were carried out in the Biebrza valley in the 1960s (Okruszko 1990; Okruszko, Byczkowski 1996). The processes described are long-term (yearly or multi-year). At the same time, in wetlands, both anthropogenic and natural phenomena, short-term or even sudden, are also observed, which, despite their short duration, cause long-term changes in the wetland ecosystem. These include mowing large areas of low vegetation and, above all, fires (Chambers *et al.* 2005; Neary *et al.* 2005; Li *et al.* 2014; Loehman *et al.* 2014; Kettridge *et al.* 2015; McKendry *et al.* 2019; Hantson *et al.* 2020; Huang *et al.* 2021; Ponomarev *et al.* 2021; Lee *et al.* 2022; Sondej, Domisch 2024).

This study aims to analyse the impact that the fire (and consequent complete burning of vegetation) on April 20–25, 2020 had on the intensity of net CO<sub>2</sub> exchange (net ecosystem exchange, NEE) between the substrate and the atmosphere. It also analyses the impact of the fire on the temporal variability of NEE components, i.e., ecosystem respi-

ration (Reco) and gross primary production (GPP). The analysis was based on the results of long-term, regular measurements of greenhouse gas exchanges conducted by the Department of Meteorology and Climatology of the University of Łódź at the measurement station in Kopytkowo (Middle Basin of Biebrza NP) since 2012 (Pawlak *et al.* 2016, 2024; Siedlecki *et al.* 2016; Fortuniak *et al.* 2017, 2021, 2023, 2026; Górowski *et al.* 2025). In April 2020, a fire occurred in the immediate vicinity, completely burning the low vegetation (Fig. 1B). The study used data from 2017–2020, supplemented with leaf area index (LAI) measurement results taken during the growing seasons.

## Study area

Located in north-eastern Poland, Biebrza National Park was established in 1993. It covers 592 km<sup>2</sup>, and its main task is to protect an extremely valuable natural fragment of the Biebrza River valley with extensive wetlands, the largest in Central Europe. Regarding the morphological features of the protected section of the valley, the park area has been divided into three units called Basins: Lower, Middle and Upper (Okruszko 1990; Okruszko, Byczkowski 1996). The station measuring fluxes of greenhouse gases (carbon dioxide and methane) (located 53°35'30.8"N, 22°53'32.4"E, 109 m a.s.l.) and belonging to the Department of Meteorology and Climatology of the University of Lodz began continuous operation in November 2012 (Fig. 1B) (Pawlak *et al.* 2016, 2024; Siedlecki *et al.* 2016; Fortuniak *et al.* 2017).

The station is surrounded by typical wetland vegetation dominated by sedges and rushes. Several residential and agricultural buildings are located ~300–400 m to the south-east. Notably, CO<sub>2</sub> emissions from their chimneys do not interfere with measurements of the natural exchange of this gas between the wetland and the atmosphere due to their significant distance and location outside the source area of the fluxes (Footprint) (Fig. 1A). Between the buildings and the station, there flows a small, completely overgrown stream called Kopytkówka (for further details, see Pawlak *et al.* 2016, 2024; Siedlecki *et al.* 2016; Fortuniak *et al.* 2017, 2021, 2023, 2026; Górowski *et al.* 2025).

On April 20–25, at the beginning of the growing season, a massive fire swept through the Middle Basin of Biebrza NP, completely burning up the vegetation in the vicinity of the measuring station in Kopytkowo (Fig. 2BC). The fire covered

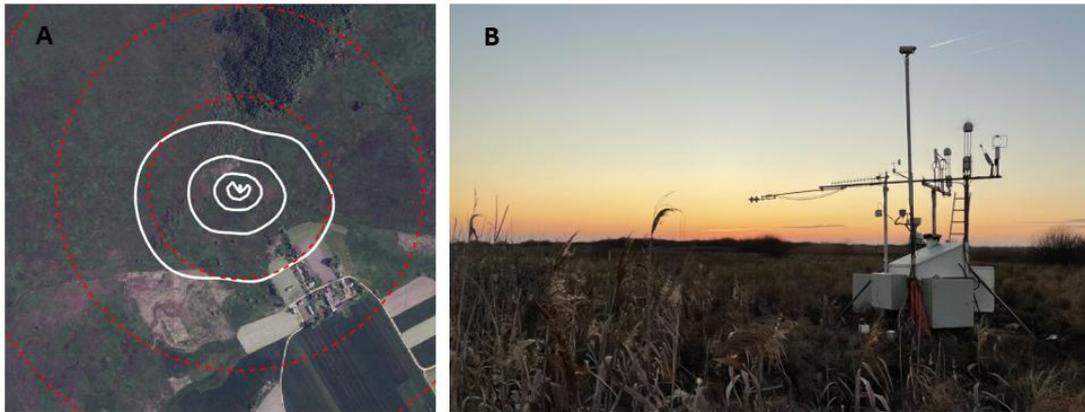


Fig. 1. A – Source area of CO<sub>2</sub> turbulent fluxes calculated for unstable conditions in the period 2017–2020 (white solid lines indicate source area with p=25, 50, 75 and 90%, red dashed lines indicate 250 and 500 m distance from the measurement site)  
B – Measurement site at Kopytkowo, Biebrza National Park (photo by W. Pawlak 2019)

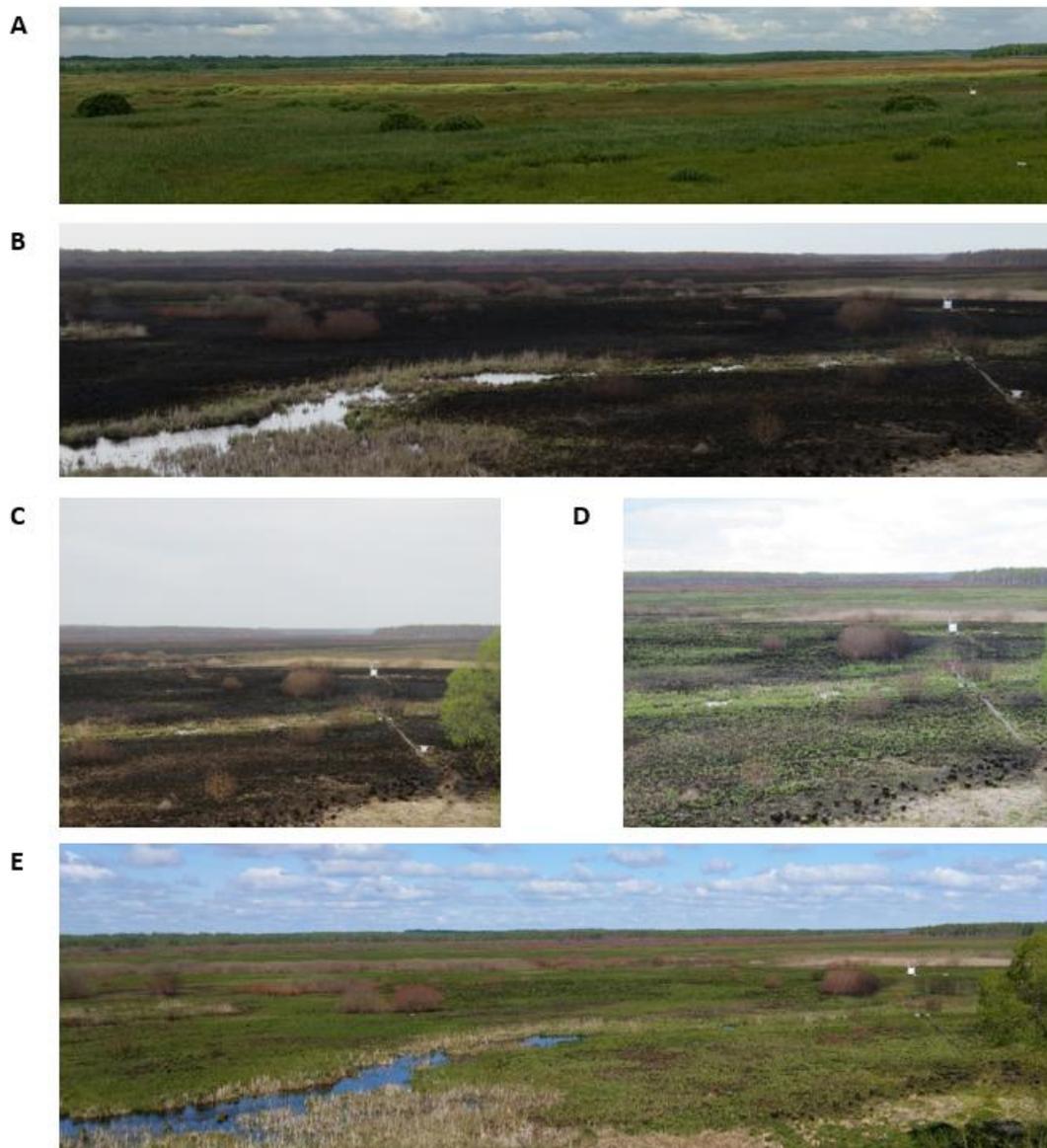


Fig. 2. The surroundings of the CO<sub>2</sub> flux measurement station in Kopytkowo (white dot in the pictures) at the beginning of: A – April 2020, B – 1<sup>st</sup> May, C – 8<sup>th</sup> May, D – 15<sup>th</sup> May, E – 21<sup>st</sup> May (photo by W. Pawlak and K. Fortuniak 2020)

~5,500 ha, less than 10% of the park's total area. The fire partially damaged the station, but CO<sub>2</sub> flux measurements resumed just one week after the fire was extinguished (Fortuniak *et al.* 2026).

Just before the fire, the vegetation around the station was in a growth phase (Fig. 2A), as is typical of the early stage of the growing season – as in previous years. As with fires recorded in other wetlands, the plants regrew very quickly after being almost completely burned. The first signs of renewed growth of sedges and rushes appeared about two weeks after the fire (Fig. 2D), and, after another two weeks, traces of the fire were visible only in selected, small areas surrounding the measurement station (Fig. 2E).

## Methodology and instrumentation

Continuous measurements of vertical CO<sub>2</sub> fluxes at the Kopytkowo station were performed using the eddy covariance (EC) technique (Stull 1988; Lee *et al.* 2005; Foken 2008; Burba 2010; Aubinet *et al.* 2012). This method, considered the most suitable for long-term measurements of ecosystem-scale CO<sub>2</sub> fluxes, allows the acquisition of data on the intensity and return of exchange at regular intervals (in this case, every hour). Positive flux values indicate net CO<sub>2</sub> release into the atmosphere, whereas negative values indicate net uptake of carbon dioxide. According to the theoretical basis of the method (Stull 1988; Lee *et al.* 2005; Foken 2008; Burba 2010; Aubinet *et al.* 2012), measurements of variables necessary to calculate the final flux values must be taken at a frequency of at least 10 Hz, which requires the use of a set of measuring instruments other than those used at standard meteorological stations. Therefore, an ultrasonic anemometer (RMYoung 81000, USA) and an LI7500 gas analyser (Licor, USA) were installed at the Kopytkowo station at 3.7 m above ground to measure the vertical component of wind speed, water vapour, and CO<sub>2</sub> concentrations. The data were recorded by a CR5000 datalogger (Campbell Scientific, USA) and then archived on a PC. In accordance with the methodology, the final CO<sub>2</sub> flux calculations took into account all necessary corrections: maximisation of covariance attributable to the separation of sensors (Kaimal, Finnigan 1994), spike detection (Vickers, Mahrt 1997), double rotation of the wind coordinate system (Kaimal, Finnigan 1994) and elimination of the influence of air humidity on the

ultrasonic anemometer measurement (Schotanus *et al.* 1983), of the influence of changes in air density, “WPL correction” (Webb *et al.* 1980) and of spectral losses (Lee *et al.* 2004; Burba 2010). The obtained data were subjected to quality assessment procedures, including three tests for stationarity of series (Foken, Wichura 1996; Mahrt 1998; Dutaur *et al.* 1999; Affre *et al.* 2000). Since the EC method does not produce results during precipitation and in conditions of insufficiently developed turbulence, the missing data were supplemented using an extended gap-filling technique (for details, see: Fortuniak *et al.* 2017, 2021). The Schmid method (1994) was also used to estimate the extent of the CO<sub>2</sub> source area (Fig. 1B), which allowed us to conclude that the measurements were not affected by anthropogenic CO<sub>2</sub> emissions from houses in the vicinity (Fig. 1). The calculations were performed using the EddyPro application (Licor, USA) and our own procedures written in Fortran and Matlab.

The EC method allows the determination of the net ecosystem exchange (NEE), i.e., the net CO<sub>2</sub> flux (Lund *et al.* 2010; Aubinet *et al.* 2012; Baldocchi 2018), which is the difference between the respiration of the ecosystem (Reco) and the gross primary production (GPP):

$$NEE = Reco - GPP \quad (1)$$

Unfortunately, the EC method cannot be used to determine Reco and GPP values. They were calculated using procedures employed by many research groups worldwide (Fortuniak *et al.* 2021) with the same 1-hour time step as NEE. Additional meteorological variables such as air temperature and humidity, atmospheric pressure, precipitation, soil temperature, radiation balance and its short- and long-wave components, and photosynthetically active radiation (PAR) were also measured at the Kopytkowo site (Fortuniak *et al.* 2023; Górowski *et al.* 2025). Measurements were taken every five minutes. During the growing season, the leaf area index LAI was also measured at 10 cm above ground using an LAI 2200C Plant Canopy Analyser (Licor, USA). Since LAI measurement is manual and cannot be automated, several measurement campaigns were carried out in selected parts of the growing season (Table 1). Because two vegetation types dominate the vicinity of the measurement site in Kopytkowo, LAI measurements were carried out for sedges and reeds.

## Results and discussion

### Variability of selected variables determining CO<sub>2</sub> exchange

In 2017–2020, air temperatures were characterised by variability typical of north-eastern Poland (Fig. 3). Both in 2017–2019 and in the year of the fire, winter temperatures reached  $-20^{\circ}\text{C}$ , while summer temperatures exceeded  $+30^{\circ}\text{C}$ . Photosynthetically active radiation (PAR) was characterised by similar regular variability (Fig. 3). Its values in the colder parts of the year did not exceed  $500 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ . In comparison, the maximum values observed in June and July reached  $2000 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  in both 2020 and the years before the fire. At the Kopytkowo measuring station in 2017 (Fig. 3), the groundwater level fluctuated around 0 cm in autumn and winter, falling to  $-40$  cm (below ground) in spring and summer.

In subsequent years, the differences were greater and the periods of low groundwater levels were longer. In 2018, the water table level (WTL) began declining in the spring and reached  $-85$  cm by the turn of summer and autumn. Heavy rainfall in July led to only a short-term rise in the groundwater level from approximately  $-20$  cm. In the year preceding the fire, WTL variability indicated a developed drought. High WTD persisted until the beginning of summer, then fell to  $-90$  cm in the following months. The reason for the prolonged periods of low WTL values lies in reduced summer precipitation, but above all in very low winter snowfall (Fortuniak *et al.* 2017, 2021, 2026; Pawlak *et al.* 2024).

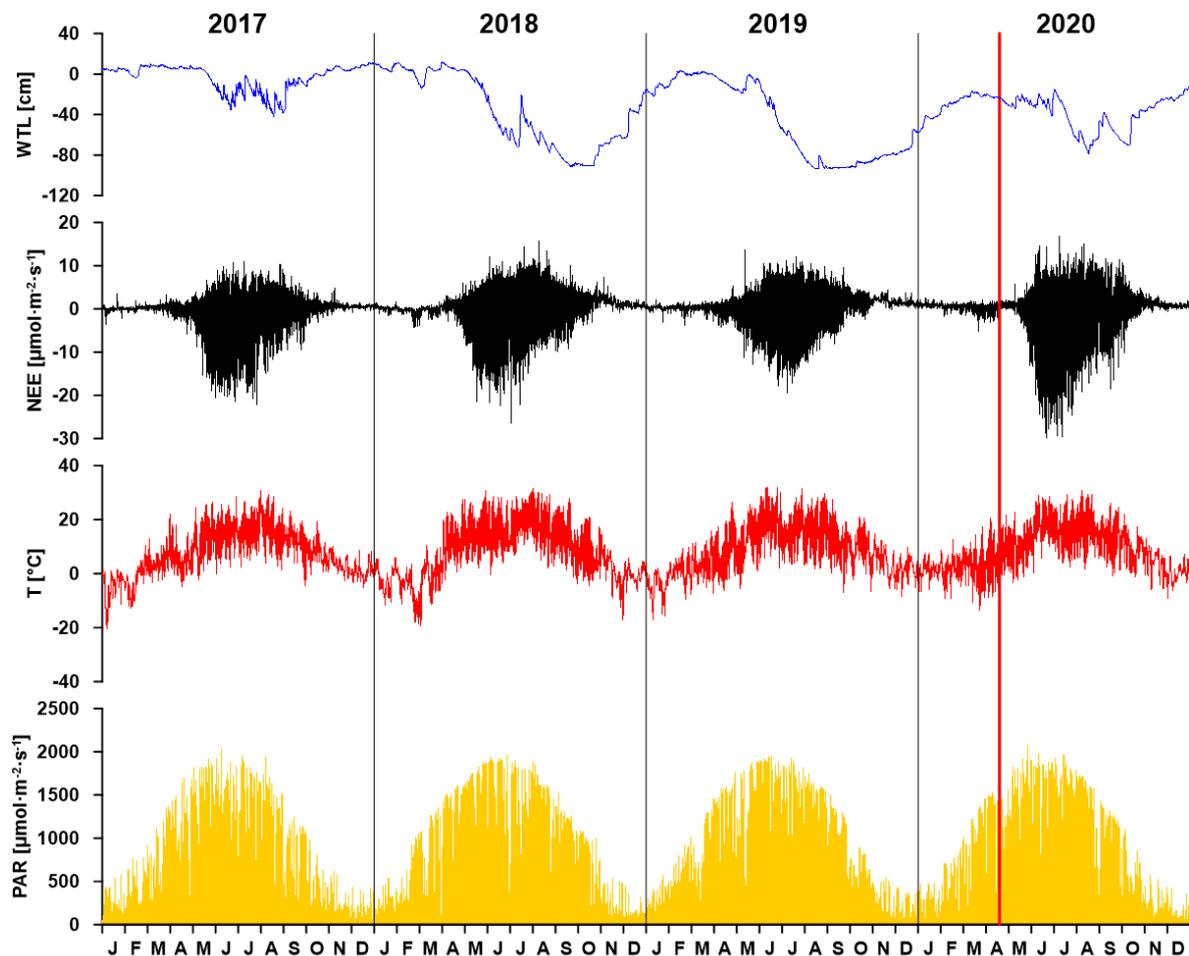


Fig. 3. Variability of 1-hour CO<sub>2</sub> water table level (WTL), net CO<sub>2</sub> exchange (NEE), air temperature (T), and photosynthetically active radiation (PAR) in the period 2017–2020  
Red line indicates wildfire dates (20–25 April 2020)

Table 1

Leaf Area Index (LAI) measurement dates and values at 10 cm above ground

Date	LAI (sedges)	LAI (reeds)
2017.05.05	0.340	0.420
2017.05.24	2.125	1.916
2017.06.20	4.014	3.908
2017.07.12	4.292	6.274
2017.07.30	4.380	4.821
2017.08.19	3.644	4.418
2017.09.14	2.583	4.084
2017.11.10	2.795	1.602
2017.12.13	0.883	1.444
2018.04.20	0.281	3.032
2018.05.10	1.899	1.851
2018.06.12	3.851	5.526
2018.06.29	5.977	6.536
2018.07.19	4.065	6.571

Date	LAI (sedges)	LAI (reeds)
2018.08.29	6.112	6.170
2018.10.02	3.517	4.360
2018.11.05	4.845	4.302
2019.03.12	4.050	1.610
2019.04.24	2.910	1.780
2019.05.07	0.780	2.950
2019.05.30	1.130	3.930
2019.06.26	4.580	5.840
2019.08.06	3.020	3.740
2019.09.05	5.950	5.210
2019.11.12	3.510	7.270
2020.07.01	7.200	9.090
2020.09.09	10.900	7.910

Unlike in previous years, the WTL did not rise as much in the winter of 2019/20. In the summer of 2020, the water table level was higher. The minimum WTL value was -80 cm twice, but both episodes were episodic (in August and October). The LAI values measured during the growing seasons in 2017–2019 (Fig. 4, Tab.1) differed markedly from those measured in the summer of 2020.

In 2017 and 2018, the variability of LAI measured in sedges and reeds was characterised by distinct seasonal variability with low values in spring and autumn, ranging from 2–3 regardless of vegetation type to 4.3–6.3 for sedges and rushes in 2017, and ~7 for both vegetation types in 2018. The year 2019 was characterised by similar LAI values to those of 2017 and 2018, but the seasonal rhythm was poorly marked. In 2020, LAI was measured only twice, after the plants had regrown from the fire. In both cases, the values were very high, between 7.2 and 10.9, indicating better conditions for new plants development (more biomass) than in previous years.

### NEE variability

During the study period, CO<sub>2</sub> flux variability was typical for wetlands covered with marsh vegetation. In winter, due to the lack of photosynthesis (low air temperature, low PAR values), hourly NEE values were close to 0  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  (Fig. 3). In spring, with the beginning of the growing season, CO<sub>2</sub> exchange intensified. There were negative NEE values during the day, indicating that carbon dioxide uptake by plants during photosynthesis prevailed over respiration, and positive values at night, when the ecosystem respire and

photosynthesis does not occur. In 2017 and 2018, the highest negative NEE values reached -20  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  and were observed from May to July. The highest positive values, on the other hand, were in the summer and reached +10  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ . In 2019 (Fig. 3), due to drought, CO<sub>2</sub> uptake was not as intense. NEE values rarely exceeded -15  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ , with the highest values observed in July. Respiration was characterised by similar intensity, with maximum NEE values of +10  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ . In 2020, NEE variability initially looked identical. After winter stagnation, exchange began to intensify, reaching values of +1  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  and -4  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  in mid-April. Immediately after the fire, due to the complete burning of plants, CO<sub>2</sub> exchange halted for about three weeks. With the regrowth of plants in early May, a very rapid increase in CO<sub>2</sub> uptake from the air was recorded, and NEE values, unlike in previous years, reached -30  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  in June and July.

### NEE component variability

As mentioned earlier, net CO<sub>2</sub> exchange results from two simultaneous processes: respiration (Reco) and gross primary production (GPP). In the years preceding the fire, the variability of these components, similar to NEE, was characterised by a distinct annual rhythm (Fig. 4). Outside the growing season, both respiration and biomass growth are very limited (Fortuniak *et al.* 2023). The daily Reco totals determined for this study for the period from November to March/April were close to 0.

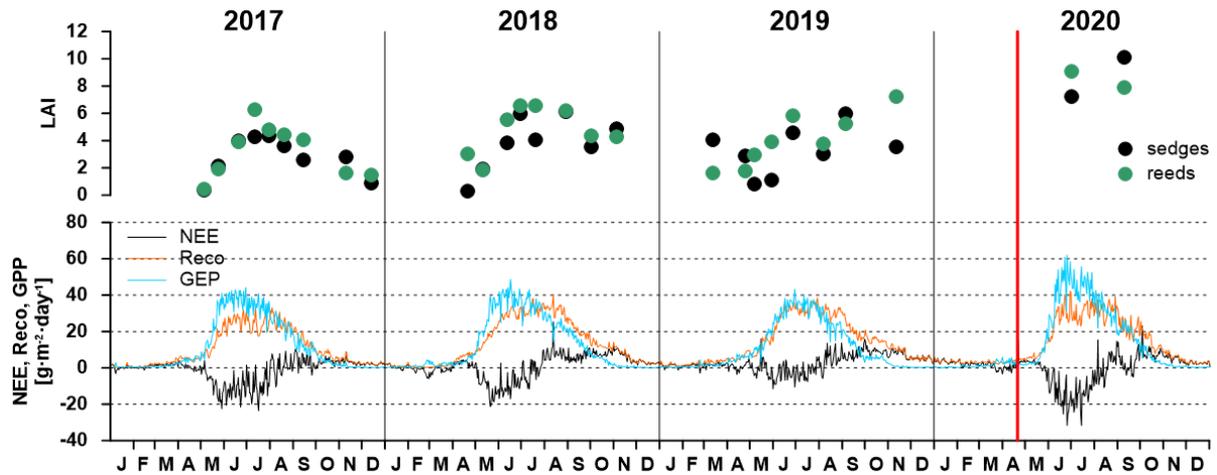


Fig. 4. Results of LAI measurements (upper row) and diurnal totals of net ecosystem exchange (NEE), gross ecosystem production (GPP), and respiration (Reco) (bottom row) in the period 2017–2020. Red line indicates wildfire period (20–25 April 2020)

Subsequently, ecosystem respiration in the vicinity of the measurement station in Kopytkowo increased until, in the summer, it reached a maximum of  $30 \text{ g}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$  in 2017 and  $\sim 40 \text{ g}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$  in 2018 and 2019. The variability in gross primary production was slightly different (Fig. 4). With the daily increases in temperature and PAR, photosynthesis increased markedly, leading to rapid plant growth. In 2017 and 2018, this process was more intense than respiration, and CO<sub>2</sub> uptake by plants reached a maximum of  $+40 \text{ g}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$  at the transition from spring to summer. During this period, the most significant negative net NEE values were observed. In 2019, when drought dominated, the daily values of Reco and GPP were similar to each other. The fire in April 2020, on the other hand, caused significant differences in the variability of daily Reco and GPP values compared to previous years (Fig. 4). First of all, after the fire, the ecosystem's respiration was severely limited for about a month and did not really start until the end of May (in previous years it was April). The daily maximum values, on the other hand, were similar, reaching  $+40 \text{ g}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$ . Gross primary production was characterised by significantly greater intensity. Along with the dynamic growth of plants, as evidenced by high LAI values (Fig. 4), daily GPP rose rapidly to a maximum of  $+60 \text{ g}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$  at the transition of June to July, which is  $\sim 50\%$  higher than in previous years. As a result, daily net NEE values exceeded  $-20 \text{ g}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$ . In 2017, the

annual net CO<sub>2</sub> exchange was  $-430 \text{ g}\cdot\text{m}^{-2}$ . Over the following two years, as drought developed, the wetland near the measuring station shifted from a CO<sub>2</sub> sink to a CO<sub>2</sub> source for the atmosphere.

Annual fluxes amounted to  $+350 \text{ g}\cdot\text{m}^{-2}$  and  $+1020 \text{ g}\cdot\text{m}^{-2}$  in 2018 and 2019, respectively. The following year, fire-induced burning and the subsequent rapid growth of new vegetation led to intensive carbon dioxide uptake. The upward trend in annual CO<sub>2</sub> exchange was halted, reaching  $+30 \text{ g}\cdot\text{m}^{-2}$  in 2020.

The impact of the fire on the variability of NEE, Reco and GPP is also clearly visible on a daily basis (Fig. 5). In May, the average daily course of both Reco and GPP was characterised by the lowest values in the entire study period. Non-zero Reco values indicate that, after the vegetation was burned, the ecosystem's respiration was limited to CO<sub>2</sub> release from the soil. GPP values were also very low, resulting in NEE close to 0 throughout the day. In June, the average daily variability of Reco and GPP in 2020 was similar to that in 2017–2019. In the following months, especially in July, GPP values were significantly higher, reaching over  $+25 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  at noon. As a result, net exchange reached its highest values in July 2020. At midday, the average was almost  $-20 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ . Elevated GPP values in 2020 compared to the years before the fire persisted until October.

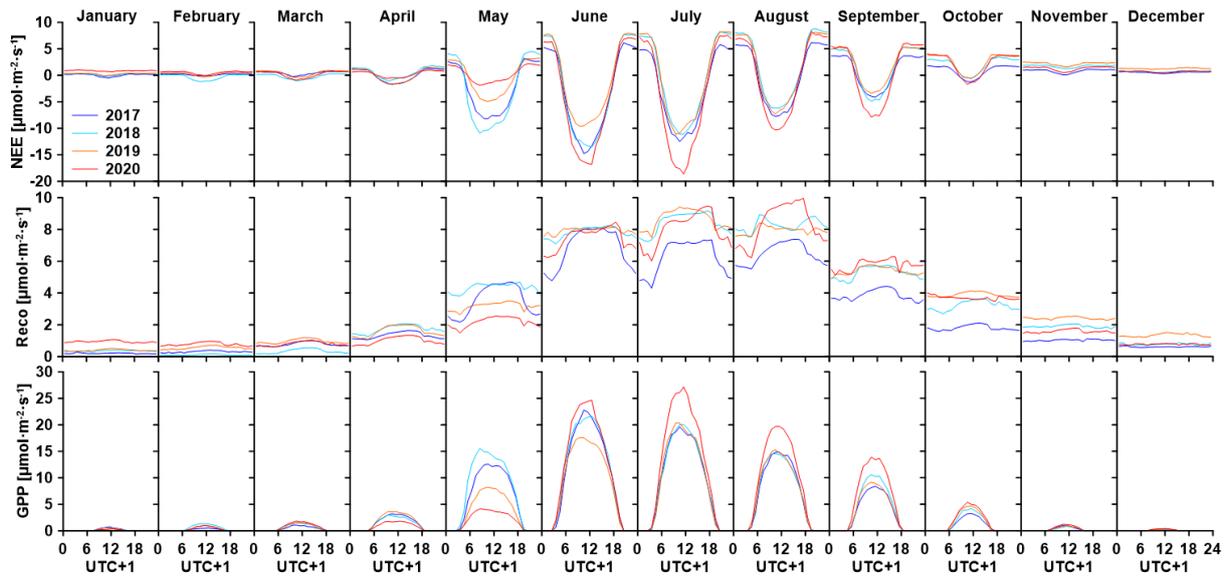


Fig. 5. Mean diurnal variability of net ecosystem exchange (NEE) (upper row), ecosystem respiration (Reco) (middle row) and gross ecosystem productivity (GPP) in the period 2017–2020

## Summary and conclusions

Fire is a phenomenon that, depending on its duration and spatial extent, can change an entire wetland ecosystem. In recent years, an increase in fire frequency has been expected due to rising air temperature, shorter and milder winters, and more frequent prolonged droughts. Fires can also have anthropogenic origins – in various wetland types (and elsewhere), fires are caused by arson, whether deliberate or accidental. Even short-lived fires can lead to more or less permanent changes in both the flora and fauna of wetland areas. These losses are often irreversible or require long-term regeneration process, especially in the animal world (Walesiak *et al.* 2022). In the case of plants, the situation is not always so dramatic, provided that it does not affect large forest complexes. The fire that struck the Middle Basin of the Biebrza Valley near the village of Kopytkowo in 2020 destroyed many hectares of low vegetation. As shown by the results of the measurements presented in the above study, the assessment of the impact of fire on CO<sub>2</sub> exchange between the substrate and the atmosphere depends on the adopted time scale. In the period of several days after the fire, CO<sub>2</sub> exchange between the ground and the atmosphere was almost completely inhibited. During this time, the gas was only released directly from the ground. In the longer term, reaching several consecutive months, the impact of the fire can be considered positive. After the sedges and rushes were burned, they regenerated and grew back

much more vigorously than in the years before the fire. As a result, this led to increased CO<sub>2</sub> uptake from the air by plants and increased gross primary production (GPP).

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