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SEASONAL AND DAILY VARIABILITY OF CO₂ EMISSIONS FROM THE CZERWONE BAGNO PEAT BOG IN BIEBRZA NATIONAL PARK (POLAND)**

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Abstract. The article describes the results of field studies carried out in the period from April 2013 to May 2014. The study concerned the assessment of the magnitude of CO₂ emissions from marsh soils in the area of Czerwone Bagno peat bog, which is a part of the largest complex of peatlands in Poland. The authors used the closed chamber method to measure seasonal variability of net ecosystem CO₂ emission and drew attention to the impact of environmental factors (air temperature, air pressure, and soil moisture) on it. The highest values of average daily CO₂ emission (over 630 mg(CO₂)×m⁻²×h⁻¹) were recorded in late spring and summer. Lowest values were obtained in late autumn and winter (in the range of 178–212 mg(CO₂)×m⁻²×h⁻¹). The need for monitoring of peat bog in temperate latitudes is stressed due to the progressive process of peat soils drying which enables the release of large quantities of greenhouse gases – CO₂, CH₄ – into the atmosphere.

Keywords: CO₂ exhalation, chamber capacity, water content, biological activity

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Peatlands, and in particular peat bogs, constitute an important link in the carbon cycle in the natural environment (Moore and Knowles 1989). Peat is the accumulated remains of plant material where the activity of decomposing organisms is suppressed by sustained or periodical waterlogging (Montanarella et al. 2006, Jarnuszewski 2016). Gorham (1991) observed that peatlands are estimated to store almost one third of the total terrestrial pool of soil carbon. As sinks of carbon dioxide and a source of methane and sulphur compounds and other greenhouse gases, peatlands play a significant role in controlling global warming (Bellisario et al. 1998). However, it is worth noticing that the considerable thickness of peat, high moisture and the cold climate restrict the possibility for greenhouse gases to escape straight to the atmosphere. On the other hand, large peatland areas occur in the temperate zone, where the intensity of gas exchange between soil and atmosphere is many times greater and results from variability of atmospheric conditions responsible for wetting and drying cycles (Borken et al. 2003). Reduced water content related e.g. to intense evaporation, drying of peatlands or changed land use may cause peatlands to be converted from a net sink to a source of CO₂ to the atmosphere (Bellisario et al. 1998, Bubier et al. 1998). The importance of moisture as a factor that determines the process of absorption or release of CO₂ from the soil has been pointed out by numerous researchers (Moore and Knowles 1989, Davidson et al. 1998, Moore and Dalva 1993, Davidson et al. 2000, McNeil and Waddington 2003). Updegraff et al. (1995) suggest that the change in carbon balance may depend on trophic status and biological activity. Other researchers list the following as important factors: variability of volumetric density and differences in the ability to retain carbon by the biomass composed of different species of organisms (Raich and Schlesinger 1992, Thomas et al. 1996), or variability of atmospheric conditions – mainly air temperature and pressure (Moore and Dalva 1993, Davidson et al. 1998, Tang et al. 2006, Riederer et al. 2014). Recent climate change predictions suggest that conditions may become drier and will affect a part of the bog carbon resource. Other factors like cloud cover and increased oceanicity, which are an effect of rising mean air temperature, may compensate for such changes (Lindsay 2010).

The most active part of peatlands, thus susceptible to carbon gases exchange, is the surface part of soil cover (Organic soils – Histosols). These soils have a surface or shallow subsurface histic or folic horizon, which consists of partially decomposed organic matter with or without admixed sand, silt and/or clay (IUSS Working Group WRB 2015, Świtoniak et al. 2016). The decomposition is retarded mainly by low temperatures or anaerobic (low oxygen content) conditions being caused by high moisture (Kabala et al. 2016).

Histosols covered ca. 3% of the land surface. In Europe, these soils occur both in lowlands (e.g. Heller and Zeitz 2012, Kalisz et al. 2010, 2015) and
mountains (e.g. Łajczak 2013, Glina et al. 2016, 2017) areas of boreal and temperate climate zones (Montanarella et al. 2006).

The primary aim of this study was to determine the influence of natural conditions on the variability of releasing CO$_2$ from peat soils during both nights and days. The study includes a reference to the specific functions of peat bogs as protected areas, which are not subject to any anthropogenic influence, other than maintenance (mowing the plants after the vegetation cycle has finished). Secondary aims were to draw attention to the importance of natural and technological factors responsible for the rate of CO$_2$ emission to the atmosphere. Furthermore, to point to the most important aspects that are omitted by many researchers or result in frequently observed methodological errors.

The first problem which concerns most studies into the gas exchange between soil, water and atmosphere is the lack of standardisation of emission values, which makes it difficult to compare the results. The most frequently used units include [mg or g (CO$_2$)×m$^{-2}$×h$^{-1}$ or s$^{-1}$] (Moore et al. 2002, Rochette-and Hutchinson 2005, Tang et al. 2006, Huth et al. 2012, Urbanova et al. 2013, Toloczko and Niewiadomski 2015) or [µm (CO$_2$)×m$^{-2}$×s$^{-1}$] (McNeil and Waddington 2003, Juszczak et al. 2012, Nagano et al. 2013). It is related to the different temporal ranges of the measurements and the applied method of calculating the emission value.

There are 2 approaches:

- short-period measurements, which last from several dozen seconds (Jauhiainen et al. 2012, Urbanova et al. 2013) to several dozen minutes (Kutzbach et al. 2007, Tołoczko and Niewiadomski 2015) and even to 4–6 hours (Tołoczko and Niewiadomski 2010) – depending on the chamber size and the measurement technique used (open or closed chambers);

Parkin and Venterea (2010) suggest that calculations of the annual emissions must be provided by measurements made at regular time intervals (every 1 or 2 weeks).

However, long-term measurements in the case of organic soils could bring a significant error, which is omitted in the deliberations. It concerns the peat tendency to swell as a result of changing moisture. Oleszczyk and Brandyk (2008) showed a close correlation between the processes of shrinking and swelling in relation to moisture changes and observe that peats in particular show a high potential for shrinking with reduced moisture and for swelling in the opposite situation. As a result, it may influence the chamber capacity parameter, which is defined as a constant value in the calculations. Susceptibility of peat to swelling, in closed chamber measurements may result in increased gas pressure and thus restrict the soil emission value as a result of the pressure. Studies conducted so
far with the use of long-term measurements have not accounted for such considerations (Niewiadomski and Tołoczko 2016). It was only the research by Jauhiainen et al. (2012) which included periodical measurement of volumetric density and assessment of the chamber’s tightness. However, it is worth noticing that the very short measurement period for soil emission of CO$_2$ (81 seconds) eliminated the problem in question. Bubier et al. (1998) describe how they installed aluminium flanges in the autumn of 1995, in order to be able to start chamber measurements after the thaw period (from April 15 to October 23). Without taking into consideration the variability of the aforementioned parameters it is difficult to prove that tightness of the chamber which was moved from place to place was sufficient for evaluating the size of CO$_2$ streams, and that the chamber’s capacity was identical at all times. Similar problems have neither been noticed nor eliminated by other researchers who conducted measurements in organic soils (Lafleur et al. 2001, Lauber-Sauheittl et al. 2014).

A convenient solution for the problem is to apply column measurements, in which the collected peat samples are placed in specially prepared pipes, made usually of PVC or Plexiglass, with specific parameters (Moore and Dalva 1993, Boardman et al. 2011). The only problem appears to be the method of referring the laboratory conditions to natural ones, considering the difficulty to preserve all the characteristic properties of organic matter. It can be helpful to consider micrometeorological studies based on eddy covariance, in which no measurement chambers are used, and the concentration measurements are conducted directly above the ground at a predefined height, taking into account the vertical component of wind velocity and measurements of pressure, temperature and soil moisture (Jacobs et al. 2003, Pawlak et al. 2012, Pawlak et al. 2016, Fortuniak et al. 2017).

Another issue related to the swelling and shrinking capability of organic soils, beside time measurement, is the chamber’s capacity. For low capacity chambers, error resulting from varying soil volume may be larger than for high capacity ones. Chamber capacity is highly variable, depending on the apparatus and ranges from 0.003 m$^3$ for short-term measurements (Wroński 2015) to nearly 20 m$^3$ in three-year studies (Johnson et al. 2001).

MATERIALS AND METHODS

Study area

The study was conducted from 24 April 2013 to 28 May 2014 in the area of the Czerwone Bagno Nature Reserve. The measurement station is located near the village of Kopytkowo ($\phi = 53^\circ35'20''$ N, $\lambda = 22^\circ53'31''$ E), located in the central part of Biebrza National Park, in the south-eastern margin of a fluviogenic valley (Fig. 1). The peat bog belongs to the geomorphologic unit of
the Biebrza Basin, which is a vast, shallow depression with the area of approx. 2,600 km², length of approx. 100 km and width of 10–20 km (Kondracki 2013). The Czerwone Bagno Reserve, established in 1926, covers an area of approximately 116 km². It is mostly taken up by diverse peat-forming plants community (with *Sphagnum* (L.) species, *Phragmites australis* (L.), *Typha latifolia* (L.), *Typha langustifolia* (L.)), and by hornbeam and riparian forests on areas of sand dunes.

Measurements were conducted directly on flat ground, without the need to remove vegetation by cutting. The soil cover of the study site consisted mainly of Sapric Histosols. Peat thickness at the site and in its direct vicinity ranged from 1.5 to 2.5 m. During the whole year the soil reaction was strongly acidic. Ground water level throughout the measuring period was several centimetres below ground level due to constant supply from the Kopytkówka River (Fig. 2), which runs across the eastern part of the reserve. The soils in the Czerwone Bagno are based on sandy formations, mainly aeolian sands and locally occurring sands and gravels of upper accumulation plains. Most of the data were collected under good weather conditions without rainfall and with sufficient radiation. Weak data due to rainfall or cloudy conditions were excluded (Falkowski and Złotoszewska-Niedziałek 2008).
Description of emission calculation

The measurements were conducted using a closed-static chamber (Figs. 3, 4). The measurement kit includes:

- Steel square frame with a 25-cm long outer side and a 21-cm long internal one, which was the basis of the chamber. The frame consists of 4 U-shaped drainpipes with a width of 2 cm from the bottom with a welded 3 cm flange to allow static positioning of the frame in the ground. It was installed consistently in the same place. The flange steel frame cuts to study a fragment of the ground surface measuring 0.0529 m².

- The transparent chamber made of Plexiglas with 23-cm long and 20-cm high sides, which gives a total capacity of 0.01058 m³. During the meas-
urements the chamber was not covered to allow normal respiration processes and CO$_2$ assimilation by plants. This is why the net ecosystem CO$_2$ emissions (NEE) were measured.

- The frame made of steel wire with a diameter of 2 mm, on which the gas concentration gauges were placed. To keep the same distance from the ground the gas gauge is to be placed at the feet in a steel drainpipe before each measurement.

- In the chamber a small fan supporting the diffusion of gases and preventing their stratification was installed. To one side of the chamber an RJ-9 connector to power the fan was attached. The 12V battery was used to power the fan. The chamber is attached directly onto the frame installed in the ground. In order to seal the assembly, water is poured into the drainpipe.

- The measuring instrument used to determine the CO$_2$ exhalation was an infrared gas analyzer (IRGA) – model AirTech Vento with a slot module for air temperature measurement.

Precise placement of the chamber was very important for measurements on an organic base. Low volumetric density of the ground makes it difficult to correctly position the steel frame – the base of the chamber. Using substantial force, e.g. the body weight, results in a temporary compaction, responsible for increased density of the outer layer of the soil. This results in reduced porosity around the flange inserted into the soil and may adversely impact the estimation of the value of CO$_2$ emission. This is why the frame was installed with the use of a light, rubber rammer in the form of a hammer, approximately 6 hours before commencing the measurements.
Studies were conducted in 2–5-day measurement sessions (Figs. 5, 6). Measurements were conducted both in the daytime (in all measurement periods) and at night (in spring and summer) in 30-minute sessions starting always on the hour. Choosing the best time interval for the measurements depends on two opposing effects (Koskinen et al. 2014). A shorter time period in principle provides a more linear concentration curve. Theoretically, the CO$_2$ concentration during the chamber closure reaches a peak due to the decreasing concentration difference between the soil and the atmosphere. To eliminate the variable closing time of the chamber and the possible inertia of the gauge, it was decided to use the 12 minutes interval between the 1$^{\text{st}}$ and 13$^{\text{th}}$ minutes as the measurement period. All datasets were filtered after regression analysis using the standard deviation of the residuals of the linear regression function as an indicator of experiment noise. It showed that longer measurement periods tend to disturb the linearity of CO$_2$ concentration increase in the chamber, which was pointed out by Schneider et al. (2009) or Kutzbach et al. (2007), as it resulted in underestimation or overestimation of the soil emission value.

The mean values of temperature and pressure during each 12-minute measurement period were used in calculations. Such an approach causes a significant diversification of CO$_2$ emission values, even if the difference of concentrations as per gauge readouts at the beginning and end of the measurement was identical for different times of day. Many authors suggest that temperature as well as other atmospheric factors influence the CO$_2$ exhalation process (Davidson et al. 1998, Tang et al. 2006, Riederer et al. 2014). Parkin and Venterea (2010) claim that temperature differences can have a marked effect on biological activity. The temperature also impacted on the absorption or emission of dissolved soil gases in water.

The CO$_2$ emission values ($E$) were calculated on the basis of Calpeyron’s ideal gas law equation which was adapted to take into account the size of the chamber. The equation assumes the following form:

\[
E = \Delta S \cdot \frac{F \cdot M_{\text{gas}}}{X \cdot K} = \Delta S \cdot \frac{n_C \cdot 10^{-6} \cdot M_{\text{gas}}}{X \cdot K}
\]

\[
[E] = \left[ \frac{\text{ppm}}{h \cdot m^2} \right] \cdot \left[ \frac{\text{mol}}{ppm^{-1} \cdot g(CO_2) \cdot mol^{-1}} \right] = \left[ \frac{g(CO_2)}{h \cdot m^2} \right] = \left[ g(CO_2) \cdot h^{-1} \cdot m^{-2} \right]
\]
where:

\( E \) – exhalation in \( [\text{mg (CO}_2\text{)} \cdot \text{m}^{-2} \cdot \text{h}^{-1}] \),

\( \Delta S \) – increase of concentration as the difference of indications from the gauge [ppm],

\( F \) – the number of moles of gas corresponding to 1 ppm; \( F = n_c \cdot 10^{-6} \) [mole×ppm\(^{-1}\)],

\( n_c \) – the number of moles of air in the measuring chamber according to current air pressure and temperature [mole],

\( M_{\text{gas}} \) – mole mass of the investigated gas; \( MCO_2 = 44.01 \) [g ∙ mole\(^{-1}\)],

\( X \) – the conversion of \( \Delta S \) measurement from minutes to a full hour – in this case: \( X = 12/60 \) [min] = 0.2 [h],

\( K \) – the area of chamber = 0.0529 [m\(^2\)].

A detailed description of the emission calculations was presented in the work by Tołoczko and Niewiadomski (2015).

Example:

Data: \( T = 296 \) [K], \( p = 101800 \) [Pa], \( \Delta S = 600 \) [ppm], time of measurement \( CO_2 = 12 \) minutes

\[
E = \Delta S \cdot \frac{F \cdot M_{\text{gas}}}{X \cdot K} = \Delta S \cdot \frac{n_c \cdot 10^{-6} \cdot M_{\text{gas}}}{X \cdot K} = 600 \cdot \frac{101800 \cdot 0.00969}{\frac{8.31 \cdot 296}{0.2 \cdot 0.0529} \cdot 10^{-6} \cdot 44.01} = \\
= 600 \cdot \frac{0.401 \cdot 10^{-6} \cdot 44.01}{0.2 \cdot 0.0529} = 1.001 [g(CO_2) \cdot h^{-1} \cdot m^{-2}] = \\
= 1001 [mg(CO_2) \cdot h^{-1} \cdot m^{-2}]
\]

RESULTS AND DISCUSSION

Determining the daily exhalation variability also poses numerous problems for the researchers. They result from difficulties related to conducting automated measurements at night. Kutzbach et al. (2007) indicate that the problems are related to changeable atmospheric conditions – reduced wind velocity and the accompanying very low value of vertical gas stream, which makes it impossible to precisely determine the emission value using the Eddy covariance technique, commonly used in exhalation studies. Due to the often very short measurement period, researchers suggest that it be lengthened. Similar conclusions were reached by Schneider et al. (2009). This, in turn, is important for the question of linearity of the \( CO_2 \) concentration progress in the measurement chamber, whose capacity may prove to be very low. Application of the linear regression function in such cases can be unreliable (Welles et al. 2001, Nakano et al. 2004, Kutzbach et al. 2007, Koskinen et al. 2014), although in recent years several solutions have been proposed that are related to the use of non-linear functions, e.g. square or exponential ones (Kutzbach et al. 2007, Parkin and Venterea 2010). Researchers
notice that the problem can be avoided if manual studies are conducted. Opening the chamber after each measurement series allows for the gauges to be reset and for another series to be started, taking into account the variability of atmospheric conditions. The activity of the peat bog proved to be an important factor, since the initial measurement value in summer months in relation to the time of day or night was very diverse (Fig. 7).

![Graph showing variability of CO₂ concentration in the chamber](image)

**Fig. 7.** Variability of CO₂ concentration in the chamber on 04 Jul 2013 depending on the time of day in [ppm] for 12 minutes of the measurement of ΔS after 1 minute to the end of the 13th minute from the closure of the chamber ΔS=S₁₃−S₁

Average daily exhalation values for individual measurement periods revealed high variability. It is worth stressing that for the period of autumn and winter no night measurements were conducted (the sunset in late autumn was at about 15:30 (CET), and in winter – at 17:00 (CET) (Table 1). The highest values of average daily CO₂ emission were recorded in late spring and summer, which is potentially related to intense growth of peatland vegetation, rapid decomposition of organic matter, intense respiration of plant roots and soil microorganisms, as well as low solubility of gases in soil water, conditioned by high temperature and atmospheric pressure. Assuming that the emission value is a net stream, owing to the use of a transparent chamber, which allows uncon-
strained photosynthesis, one should expect – on the basis of results from other researchers – that the general exhalation value, exclusive of CO$_2$ uptake by the vegetation, would be higher (Bellisario et al. 1998, Alm et al. 2007). Average daily CO$_2$ emission in the summer is higher by nearly 300% than that recorded in late autumn or winter. Spring measurements are lower than summer ones by about 30–45%.

**TABLE 1. AVERAGE CO$_2$ EXHALATION VALUES AT THE MEASUREMENT STATION**

<table>
<thead>
<tr>
<th>Measurement period</th>
<th>CO$_2$ emission with regard to standard deviation in [mg(CO$_2$)×m$^{-2}$×h$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2013 Apr 24–25</td>
<td>383 ± 49</td>
</tr>
<tr>
<td>2013 May 14–16</td>
<td>368 ± 164</td>
</tr>
<tr>
<td>2013 Jun 04–06</td>
<td>676 ± 193</td>
</tr>
<tr>
<td>2013 Jul 01–05</td>
<td>633 ± 233</td>
</tr>
<tr>
<td>2013 Jul 29–Aug 01</td>
<td>554 ± 187</td>
</tr>
<tr>
<td>2013 Sep 17–18</td>
<td>220 ± 75</td>
</tr>
<tr>
<td>2013 Nov 29–30</td>
<td>178 ± 73</td>
</tr>
<tr>
<td>2014 Feb 27–28</td>
<td>212 ± 55</td>
</tr>
<tr>
<td>2014 May 27–28</td>
<td>471 ± 152</td>
</tr>
</tbody>
</table>

Average CO$_2$ emission values for each season of the year were: winter – 212 mg(CO$_2$)×m$^{-2}$×h$^{-1}$, spring – 410 mg(CO$_2$)×m$^{-2}$×h$^{-1}$, summer – 613 mg(CO$_2$)×m$^{-2}$×h$^{-1}$, and autumn – 197 mg(CO$_2$)×m$^{-2}$×h$^{-1}$. The period of exceptionally warm winter and the fewest measurements in the analysed period probably had an influence on the higher average CO$_2$ emission than in the autumn period. It is also worth noticing that the ground water level in the peat bog in autumn was very high and nearly reached the ground surface. In the winter period, the saturation of the soil was full at the depth of about 5 cm below ground surface. The onset of growth in spring is characterised by a considerable increase of average exhalation in comparison with the autumn-winter season. In the summer, when peat bog vegetation grows luxuriantly, as does the biological life in the soil, the average CO$_2$ emission from the soil was roughly three times greater than in autumn and winter.

The results obtained for the peat bog area from winter measurements in comparison with broadleaf forests, are nearly two times lower, but higher than for coniferous forests (Tang et al. 2006). Mean values for the summer period exceed the values obtained for various forest types (Tüfekçioğlu and Kϋçük 2004, Tang et al. 2006). Comparing the results to the natural habitats of hornbeam forests, Corynephoretum canescentis (L.) grasslands or fresh Arrhenatheretalia (L.) meadows, the CO$_2$ emission values from organic soils are two to four and a half higher (Krysiak et al. 2010, Papiński et al. 2010). The obtained values are close to those obtained for other peatland areas throughout the year (Moore and Dalva 1993, Koskinen et al. 2014), and also in comparison with selected periods such as winter or spring (Huth et al. 2012), or summer (Urbanova et al. 2013).
Taking into account the changing seasons, the winter soil CO₂ emission measurements were conducted in February. The exhalation value was the lowest in the analysed period. The area of the Czerwone Bagno Reserve was devoid of snow cover, as the winter in 2014 was warm. According to Seasonal Bulletin on the climate of the WMO Region VI – Europe and Middle East (2014), the total precipitation in the 2013/2014 winter was one of the lowest in several decades. The period also had lower amount of sunshine than in the previous years. Many researchers skip measurements in the winter period due to numerous technical problems and difficulties related to installing the measuring equipment in frozen ground. This concerns in particular measurements conducted in agricultural areas. One of the assumptions of chamber-based studies is that interference with natural condition of the soil cover should be minimal. Considerable thickness of snow cover impedes the installation of the kit, especially with regard to the necessity to set the chamber flange directly into the ground. Schindlbacher et al. (2014) proved that the snow cover does not have a significant impact on the average annual value of CO₂ emission from soil to the atmosphere. Vuorinen and Kurkela (1993) point out that even in winter, soils show a slight biological activity caused by the presence of fungi, whereas snow, as a sort of cover that hinders free escape of gases to the atmosphere, results in gas concentration on the ground surface. Similar results were obtained by Zimov et al. (1993) and Panikov and Dedysh (2000). On February 27 and 28, twenty CO₂ exhalation measurements were conducted. The area of Czerwone Bagno, despite the aforementioned lack of snow cover was frozen to the depth of several centimetres below ground surface. For morning hours (between 6 a.m. and noon) the exhalation values oscillated within the range of 188–315 mg(CO₂)×m⁻²×h⁻¹. In the afternoon hours (between noon and 6 p.m.), the exhalation showed even lower values, ranging between 150 and 271 mg(CO₂)×m⁻²×h⁻¹. Exhalation in the evening hours (between 6 p.m. and midnight) oscillated around 190 mg(CO₂)×m⁻²×h⁻¹. No measurements were conducted in the night hours (between midnight and 6 a.m.). The value of gaseous emission was influenced by the lowest values of air temperature in the analysed period, ground frost penetration which reduced gas exchange, as well as reduced activity of microorganisms. Significant portion of gases was trapped in the soil water, ice occurred near the measuring station in land hollows between tufts of vegetation was rich in bubbles of trapped gases (Fig. 8).

Spring measurements campaigns were conducted in April and May 2013 and in April 2014. In total, 55 half-hour measurements were taken during 6 days. Despite considerable temperature variability in these months, the exhalation values for the morning hours were similar and oscillated around 217 mg(CO₂)×m⁻²×h⁻¹ in the earliest morning, reaching the maximum of 693 mg(CO₂)×m⁻²×h⁻¹ just before noon. Average exhalation for the 6–12 period was 330 mg(CO₂)×m⁻²×h⁻¹. In the afternoon, the variability was slightly higher and ranged from 231 to 848 mg(CO₂)×m⁻²×h⁻¹, with the average value of 461 mg(CO₂)×m⁻²×h⁻¹. The meas-
measurements conducted in the evening hours showed a little lower exhalation variability, at the level of 354–620 mg\(\text{CO}_2\times m^{-2}\times h^{-1}\), with the average value of 464 mg\(\text{CO}_2\times m^{-2}\times h^{-1}\). Night measurements were conducted only twice, on May 28, 2014, and the values were 489 and 499 mg\(\text{CO}_2\times m^{-2}\times h^{-1}\). The average value of \(\text{CO}_2\) emission from soil for the spring months was 410 mg\(\text{CO}_2\times m^{-2}\times h^{-1}\).

In the summer of 2013, studies were conducted in all three months, on consecutive days: 04–06 Jun, 01–07 Jul, 29–31 Jul and on 01 Aug. A total of 108 measurements were conducted. Owing to substantial variability of thermal conditions and intense growth of vegetation, the amplitudes of \(\text{CO}_2\) emission for each time of day were high. For the morning hours, the variability range was between 258 and 986 mg\(\text{CO}_2\times m^{-2}\times h^{-1}\). The average value was 560 mg\(\text{CO}_2\times m^{-2}\times h^{-1}\). Lower than average emission values were recorded between 6 and 8 a.m., and the highest – between 10 a.m. and noon. In the afternoon, the exhalation value on the analysed days was less diverse and ranged from 409 to 942 mg\(\text{CO}_2\times m^{-2}\times h^{-1}\), with the average value of 716 mg\(\text{CO}_2\times m^{-2}\times h^{-1}\). The evening hours were characterised by a slightly greater variability. The minimum value was 250 mg\(\text{CO}_2\times m^{-2}\times h^{-1}\), while the maximum reached 972 mg\(\text{CO}_2\times m^{-2}\times h^{-1}\). The average exhalation value for the evening hours was 590 mg\(\text{CO}_2\times m^{-2}\times h^{-1}\). In the summer period, 19 night measurements were conducted, recorded amounts of \(\text{CO}_2\) oscillated between 330 mg\(\text{CO}_2\times m^{-2}\times h^{-1}\) on the last day of July and 1,006 mg\(\text{CO}_2\times m^{-2}\times h^{-1}\) at dawn on 04 Jul. The average exhalation value in the summer months was the highest of the entire period and amounted 602 mg\(\text{CO}_2\times m^{-2}\times h^{-1}\). Since the night of 31 Jul, when 3 measurements were taken, showed exceptionally
low exhalation values within the range of 330–391 mg(CO$_2$)×m$^{-2}$×h$^{-1}$, the average value was calculated without this data series. For the remaining night measurements, the average value was 726 mg(CO$_2$)×m$^{-2}$×h$^{-1}$. This might indicate extraordinary biological activity in the peat bog soils, related to high temperature and the resulting low water solubility of gases. The ground water level was the lowest of the entire analysed period, the water table did not exceed 15 cm below ground level. Moore and Dalva (1993) draw special attention to the impact of lowering the water table on the values of CO$_2$ soil exhalation and suggest a several-fold increase of greenhouse gas emission related to this process. For ground water level decrease by 10–15 cm below ground level, the emission value is relatively constant. A decrease below 20 cm resulted in a dynamic emission increase due to the release of considerable amounts of CO$_2$ dissolved in water. This is significant for the ecological condition of peat bogs, and is the reason why many researchers call for the necessity of their periodical irrigation or restoration in the event of long-lasting droughts (Moore and Dalva 1993, Glatzel et al. 2004, Lindsay 2010, Artz et al. 2013, Glina et al. 2016).

The autumn period showed high dynamics of gas exchange between the soil and the atmosphere. The studies were conducted on 17–18 Sep and 29–30 Nov. The difference between CO$_2$ emissions on both dates was almost twofold, that is why it was treated separately. In September, a total of 16 measurements were conducted, and 18 in November. In the morning hours (September), CO$_2$ exhalation was approximately 200 mg(CO$_2$)×m$^{-2}$×h$^{-1}$. In the afternoon, it changed within the range of 149 to 374 mg(CO$_2$)×m$^{-2}$×h$^{-1}$, assuming the average value of 227 mg(CO$_2$)×m$^{-2}$×h$^{-1}$. In the evening hours, the variability amounted to 153–268 mg(CO$_2$)×m$^{-2}$×h$^{-1}$, with the average exhalation of 206 mg(CO$_2$)×m$^{-2}$×h$^{-1}$. At night, no measurements were taken both in September and November. The morning hours in November were characterised by an oscillation between 124.06 and 150.11 mg(CO$_2$)×m$^{-2}$×h$^{-1}$, whereas the average value for measurements in this part of day was 137 mg(CO$_2$)×m$^{-2}$×h$^{-1}$. For the afternoon hours in September, emission values ranged from 149 to 374 mg(CO$_2$)×m$^{-2}$×h$^{-1}$, whereas in November – 117–157 mg(CO$_2$)×m$^{-2}$×h$^{-1}$. The average value for September and November reached 227 mg(CO$_2$)×m$^{-2}$×h$^{-1}$, and 139 mg(CO$_2$)×m$^{-2}$×h$^{-1}$, respectively. The variability of CO$_2$ emission in the evening hours, oscillated between 153 and 268 mg(CO$_2$)×m$^{-2}$×h$^{-1}$ in September and 152–367 mg(CO$_2$)×m$^{-2}$×h$^{-1}$ in November. The average exhalation value in September was 206 mg(CO$_2$)×m$^{-2}$×h$^{-1}$, to reach 242 mg(CO$_2$)×m$^{-2}$×h$^{-1}$ in November.

The study shows a large seasonal variability of peat bog soils CO$_2$ exhalation in the Czerwone Bagno Reserve. Great importance, in terms of the potential danger of releasing a large amount of carbon dioxide directly to the atmosphere, has a moisture of habitat and weather conditions. There is a need for constant monitoring of peatlands especially functioning as protected areas. It is necessary to identify guidelines and practical solutions in order to maintain the ecologi-
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cal balance of peat bogs in the future. Legal regulations which are limiting the possibility of interference in protected areas may cause difficulties in rational management of these ecosystems.

CONCLUSIONS

Study of CO₂ emission conducted by hundreds of researchers from around the world has contributed to the signing of several international agreements to reduce these emissions – most recently in Paris in 2015. Soils are a natural source of CO₂, and decay processes occurring in organic horizons are a natural provider of atmospheric CH₄ and other greenhouse gases. Limiting the soil respiration by international agreements restricting greenhouse gas emissions is impossible, but soil science studies show that in wet areas – swamps, peat bogs, fens and transitional mires – there is an unidentified pool of CO₂, which through the carelessness of local governments and at the beginning of the drying process may lead to an increase of the natural CO₂ release. Research provided on peat bog soils clearly shows that there is a problem of maintaining the carbon pool, which will continue to grow. The study in the Czerwone Bagno Reserve shows a large seasonal variability of soil CO₂ exhalations. Much larger CO₂ emissions from peatland soils compared with the areas of differently managed and used mineral soils may be an important factor in the discussion of the impact of naturally released greenhouse gases into the atmosphere. All environmental factors like soil moisture, temperature, air pressure, which influence the process of CO₂ release from organic soils, play an important role in the global carbon balance including CO₂ emission.

The enhanced protection of the world’s wetlands, the increasing extent of Nature 2000 areas in Europe, or supporting local initiatives by small organisations, can certainly help to minimise environmental problems related to the functioning of wetlands (including peatlands) in every latitude. Local initiatives to protect the peatlands are as valuable as administrative closing of a conventional fuel-fired boiler plants. Thanks to soil research, the great reservoir of CO₂ trapped in the wetland areas – which should not be released into the atmosphere – will have a better chance to remain undisturbed for the next decades.

REFERENCES


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