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SEASONAL AND DAILY VARIABILITY OF CO_2 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 CO_2 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 CO_2 emission and drew attention to the impact of environmental factors (air temperature, air pressureandsoil moisture) on it. The highest values of average daily CO_2 emission (over 630 mg(CO_2)×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(CO_2)×m^{-2}×h^{-1}). The need for monitoringof peat bogin temperate latitudes is stressed due to the progressive process of peat soilsdrying which enables the release of large quantities of greenhouse gases – CO_2, CH_4 – into the atmosphere.

Keywords: CO_2 exhalation, chamber capacity, water content, biological activity

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INTRODUCTION

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 CO_2 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 CO_2 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 andWaddington 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 (Kabała *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 peatsoils 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 $(CO_2)\times m^{-2}\times h^{-1}$ or s^{-1}] (Moore *et al*. 2002, Rochette-and Hutchinson 2005, Tang *et al*. 2006, Huth *et al*. 2012, Urbanova *et al*. 2013, Tołoczko and Niewiadomski 2015) or [µm $(CO_2)\times m^{-2}\times s^{-1}$] (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);
- near-continuous measurements (Ambus and Robertson 1998, Liang *et al*. 2003, Turcu *et al*. 2005).

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. Oleszczuk 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 (φ = 53°35'20" N, λ = 22°53'31" 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 km^2, 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 km^2. 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.

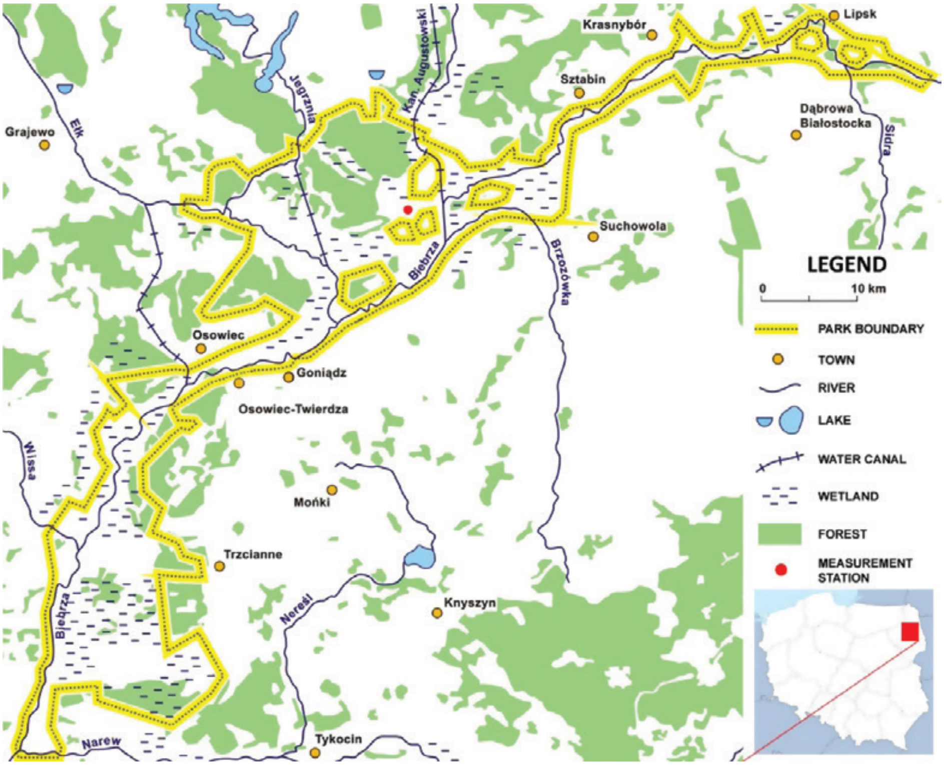

Fig. 1. Location of the measurement station in Biebrza National Park(Poland, Central Europe)

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).

Fig. 2. Panorama of the research area on: A – 01 Aug 2013, B – 30 Nov 2013, C – 28 Feb 2014, D – 27 May 2014

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 m^2.
- The transparent chamber made of Plexiglas with 23-cm long and 20-cm high sides, which gives a total capacity of 0.01058 m^3. 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.

Fig. 3. The chamber (measurements kit) 30 Jul 2013

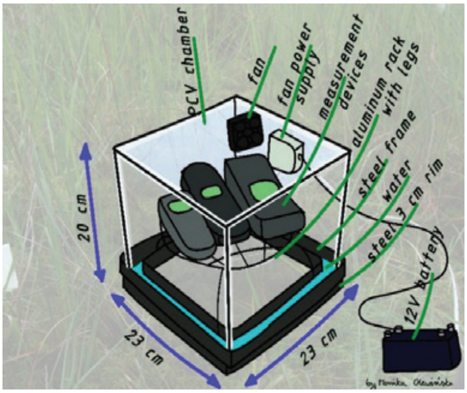

Fig. 4. Scheme of the measurement chamber

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.

Fig. 5. Measurements – 15 May 2013

Fig. 6. Measurements – 30 Nov 2013

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 1st and 13th 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:

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

$$[E] = \left[ppm \cdot \frac{mol \ \cdot \ ppm^{-1} \ \cdot \ g(CO_2)mol^{-1}}{h \ \cdot m^2}\right] = \left[\frac{g(CO_2)}{h \ \cdot m^2}\right] = \left[g(CO)_2 \cdot h^{-1} \cdot m^{-2}\right]$$

where:

E – exhalation in [mg (CO_2) · m^{-2}· h^{-1}],

ΔS – 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· 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],

Mgas – mole mass of the investigated gas; MCO_2 = 44.01 [g · $mole^{-1}$],

X – the conversion of ΔS 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], ΔS = 600 [ppm], time of measurement CO_2 = 12 minutes

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

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).

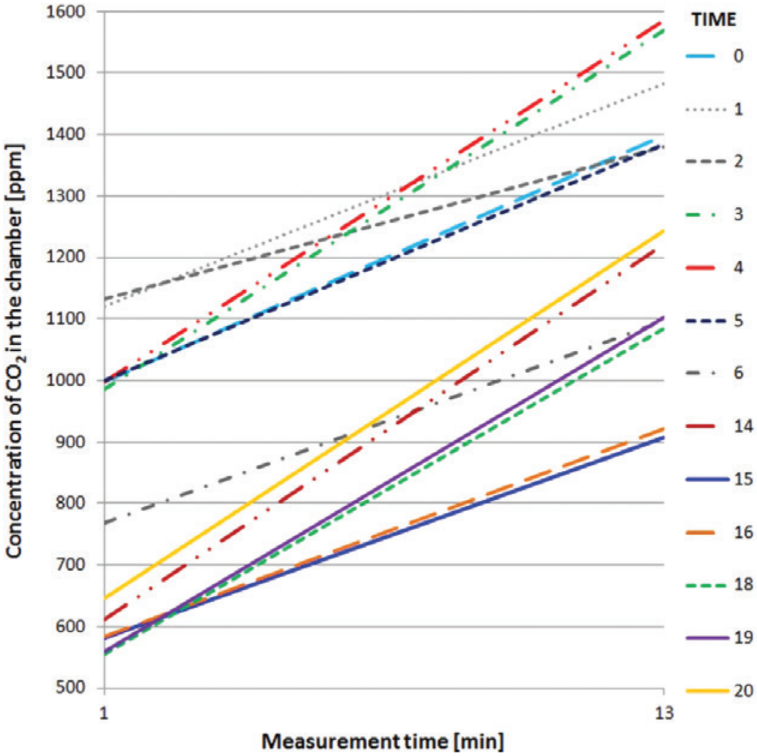

Fig. 7. Variability of CO_2 concentration in the chamber on 04 Jul 2013 depending on the time of day in [ppm] for 12 minutes of the measurement of ΔS after 1 minute to the end of the 13th minute from the closure of the chamber $\Delta S = S_{13} - S_1$

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 CO_2 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 unconstrained 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

Measurement period	CO_2 emission with regard to standard deviation in [$mg(CO_2)\times m^{-2}\times h^{-1}$]
2013 Apr 24–25	383 ± 49
2013 May 14–16	368 ± 164
2013 Jun 04–06	676 ± 193
2013 Jul 01–05	633 ± 233
2013 Jul 29–Aug 01	554 ± 187
2013 Sep 17–18	220 ± 75
2013 Nov 29–30	178 ± 73
2014 Feb 27–28	212 ± 55
2014 May 27–28	471 ± 152

Average CO_2 emission values for each season of the year were: winter – 212 $mg(CO_2)\times m^{-2}\times h^{-1}$, spring – 410 $mg(CO_2)\times m^{-2}\times h^{-1}$, summer – 613 $mg(CO_2)\times m^{-2}\times h^{-1}$, and autumn – 197 $mg(CO_2)\times m^{-2}\times h^{-1}$. 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 soilwas 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 (Tüfekçioĝlu and Küçük 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, Papińska *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 CO_2 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 CO_2 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 CO_2 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 $mg(CO_2)\times m^{-2}\times h^{-1}$. In the afternoon hours (between noon and 6 p.m.), the exhalation showed even lower values, ranging between 150 and 271 $mg(CO_2)\times m^{-2}\times h^{-1}$. Exhalation in the evening hours (between 6 p.m. and midnight) oscillated around 190 $mg(CO_2)\times m^{-2}\times h^{-1}$. 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 $mg(CO_2)\times m^{-2}\times h^{-1}$ in the earliest morning, reaching the maximum of 693 $mg(CO_2)\times m^{-2}\times h^{-1}$ just before noon. Average exhalation for the 6–12 period was 330 $mg(CO_2)\times m^{-2}\times h^{-1}$. In the afternoon, the variability was slightly higher and ranged from 231 to 848 $mg(CO_2)\times m^{-2}\times h^{-1}$, with the average value of 461 $mg(CO_2)\times m^{-2}\times h^{-1}$. The meas-

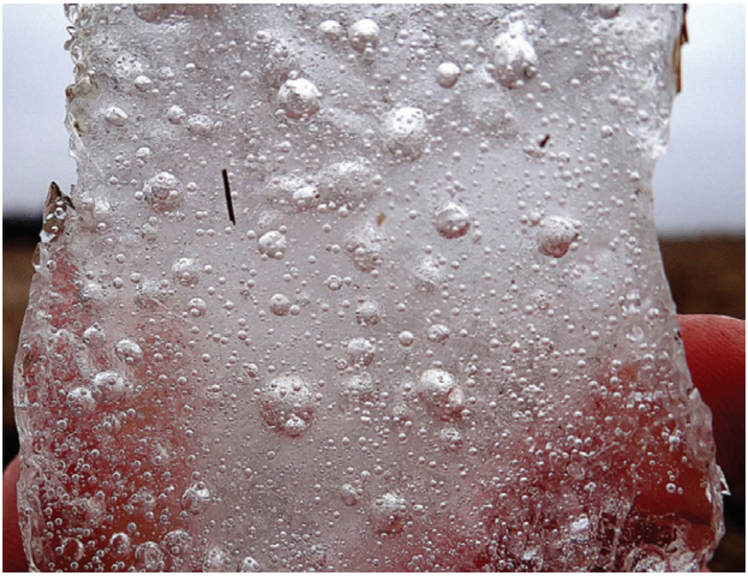

Fig. 8. Gas bubbles trapped in the ice on the peatland surface

urements conducted in the evening hours showed a little lower exhalation variability, at the level of 354–620 mg(CO_2)×m^{-2}×h^{-1}, with the average value of 464 mg(CO_2)×m^{-2}×h^{-1}. Night measurements were conducted only twice, on May 28, 2014, and the values were 489 and 499 mg(CO_2)×m^{-2}×h^{-1}. The average value of CO_2 emission from soil for the spring months was 410 mg(CO_2)×m^{-2}×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 CO_2 emission for each time of day were high. For the morning hours, the variability range was between 258 and 986 mg(CO_2)×m^{-2}×h^{-1}. The average value was 560 mg(CO_2)×m^{-2}×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(CO_2)×m^{-2}×h^{-1}, with the average value of 716 mg(CO_2)×m^{-2}×h^{-1}. The evening hours were characterised by a slightly greater variability. The minimum value was 250 mg(CO_2)×m^{-2}×h^{-1}, while the maximum reached 972 mg(CO_2)×m^{-2}×h^{-1}. The lowest values were recorded in late evening hours, and the highest – between 6 and 8 p.m. The average exhalation value for the evening hours was 590 mg(CO_2)×m^{-2}×h^{-1}. In the summer period, 19 night measurements were conducted, recorded amounts of CO_2 oscillated between 330 mg(CO_2)×m^{-2}×h^{-1} on the last day of July and 1,006 mg(CO_2)×m^{-2}×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(CO_2)×m^{-2}×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 ecological 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 CO_2 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 CO_2, and decay processes occurring in organic horizons are a natural provider of atmospheric CH_4 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 CO_2, which through the carelessness of local governments and at the beginning of the drying process may lead to an increase of the natural CO_2 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 CO_2 exhalations. Much larger CO_2 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 CO_2 release from organic soils, play an important role in the global carbon balance including CO_2 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 CO_2 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

[1] Alm, J., Shurpali, N.J., Tuittila, E-S., Laurila, T., Maljanen, M., Saarnio, S., Minkkinen, K., 2007. *Methods for determining emission factors for the use of peat and peatlands – flux measurements and modelling*. Boreal Environment Research, 12: 85–100.

[2] Ambus, P., Robertson, G.P., 1998. *Automated Near-Continuous Measurement of Carbon Dioxide and Nitrous Oxide Fluxes from Soil*. Soil Science Society of America Journal, 62, 2: 394–400, DOI: 10.2136/sssaj1998.03615995006200020015x.

[3] Artz, R.R.E., Chapman, S.J., Saunders, M., Evans, C.D., Matthews, R.B., 2013. *Comment on "Soil CO_2, CH_4 and N_2O fluxes from an afforested lowland raised peat bog in Scotland: implications for drainage and restoration" by Yamulki et al. (2013)*. Biogeosciences, 10: 7623–7630, DOI: 10.5194/bg-10-7623-2013.

[4] Bellisario, L.M., Moore, T.R., Bubier, J.L., 1998. *Net ecosystem CO_2 exchange in a boreal peatland, northern Manitoba*. Ecoscience, 5, 4: 517–525, DOI: 10.1080/11956860.1998.11682491.

[5] Boardman, C.P., Gauci, V., Watson, J.S., Blake, S., Beerling, D.J., 2011. *Contrasting wetland CH_4 emission responses to simulated glacial atmospheric CO_2 in temperate bogs and fens*. New Phytologist, 192: 898–911, DOI: 10.1111/j.1469-8137.2011.03849.x.

[6] Borken, W., Davidson, E.A., Savage, K., Gaudinski, J., Trumbore, S.E., 2003. *Drying and Wetting Effects on Carbon Dioxide Release from Organic Horizons*. Soil Science Society of America Journal, 67, 6: 1888–1896, DOI: 10.2136/sssaj2003.1888.

[7] Bubier, J.L., Crill, P.M., Moore T.R., Savage, K., Varner, R.K., 1998. *Seasonal patterns and control of net ecosystem CO_2 exchange in a boreal peatland complex*. Global Biogeochemical Cycles, 12: 703–714, DOI: 10.1029/98GB02426.

[8] Davidson, E.A., Belk, E., Boone, R.D., 1998. *Soil water content and temperature as independent or confounded factors controlling soil respiration in a temperate mixed hardwood forest*. Global Change Biology, 4: 217–227, DOI: 10.1046/j.1365-2486.1998.00128.x.

[9] Davidson, E.A., Verchot, L.V., Cattânio, J.H., Ackerman, I.L., Carvalho, J.E.M., 2000. *Effects of soil water content on soil respiration in forests and cattle pastures of eastern Amazonia*. Biogeochemistry, 48: 53–69.

[10] Falkowski, T., Złotoszewska-Niedziałek, H., 2008. *Ascertainment of the geological structure for the Czerwone Bagno reserve underground water feeding model* (in Polish). Biuletyn Państwowego Instytutu Geologicznego, Hydrogeologia, 431: 35–40.

[11] Fortuniak, K., Pawlak, W., Bednorz, L., Grygoruk, M., Siedlecki, M., Zieliński, M., 2017. *The methane and carbon dioxide fluxes on a temperate mire in Central Europe*. Agricultural and Forest Meteorology, 232: 306–318, DOI: 10.1016/j.agrformet.2016.08.023.

[12] Glatzel, S., Basiliko, N., Moore, T., 2004. *Carbon dioxide and methane production potentials of peats from natural, harvested and restored sites, eastern Québec, Canada*. Wetlands, 24, 2: 261–267.

[13] Glina, B., Bogacz, A., Gulyás, M., Zawieja, B., Gajewski, P., Kaczmarek, Z., 2016. *The effect of long-term forestry drainage on the current state of peatland soils: A case study from the Central Sudetes, SW Poland*. Mires and Peat, 18, 21: 1–11, DOI: 10.19189/MaP.2016.OMB.239.

[14] Glina, B., Waroszewski, J., Bogacz, A., Majewski, W., Kaczmarek, T., Gajewski, P., Kaczmarek, Z., 2017. *Sand removal from sandstone cliffs as the main factor influencing properties of organic soils – a case study of transitional bog in the Stołowe Mountains*. Polish Journal of Soil Science, 50, 1: 21–30, DOI: 10.17951/pjss/2017.50.1.21.

[15] Gorham, E., 1991. *Northern peatlands: Role in the carbon cycle and probable responses to climatic warming*. Ecological Applications, 1, 2: 182–195, http://www.jstor.org/stable/1941811.

[16] Heller, C., Zeitz, J., 2012. *Stability of soil organic matter in two northeastern German fen soils: the influence of site and soil development*. Journal of Soils and Sediments, 12, 8: 1231–1240, DOI: 10.1007/s11368-012-0500-6.

[17] Huth, H., Jurasinski, W., Glatzel, S., 2012.*Winter emissions of carbon dioxide, methane and nitrous oxide from a minerotrophic fen under nature conservation management in north-east Germany*. Mires and Peat, 1, 4: 1–13.

[18] Jacobs, A.F.G., Ronda, R.J., Holtslag, A.A.M., 2003. *Water vapour and carbon dioxide fluxes over bog vegetation*. Agricultural and Forest Meteorology, 116: 103–112. DOI: 10.1016/S0168-1923(02)00229-0.

[19] Jarnuszewski, G., 2016. *Characterization of some physical and chemical properties of post-bog soils developed from limnic deposits in vicinity of lake Dubie (Western Pomerania, NW Poland)* (in Polish). Soil Science Annual, 67, 1: 24–31, DOI: 10.1515/ssa-2016-0004.

[20] Jauhiainen, J., Hooijer, A., Page, S.E., 2012. *Carbon dioxide emissions from an Acacia plantation on peatland in Sumatra, Indonesia*. Biogeosciences, 9: 617–630, DOI: 10.5194/bg-9-617-2012.
[21] Johnson, D.W., Hungate, B.A., Dijkstra, P., Hymus, G., Drake, B., 2001. *Effects of Elevated Carbon Dioxide on Soils in a Florida Scrub Oak Ecosystem*. Journal of Environmental Quality, 30, 2: 501–507.
[22] Juszczak, R., Acosta, M., Olejnik, J., 2012. *Comparison of daytime and nighttime ecosystem respiration measured by the closed chamber technique on a temperate mire in Poland*. Polish Journal of Environmental Studies, 21, 3: 643–658.
[23] Kabała, C., Świtoniak, M., Charzyński, P., 2016. *Correlation between the Polish Soil Classification (2011) and international soil classification system World Reference Base for Soil Resources (2015)*. Soil Science Annual, 67, 2: 88–100, DOI: 10.1515/ssa-2016-0012.
[24] Kalisz, B., Łachacz, A., Głażewski, R., 2010. *Transformation of some organic matter components in organic soils exposed to drainage*. Turkish Journal of Agriculture and Forestry, 34: 245–256, DOI: 10.3906/tar-0905-33.
[25] Kalisz, B., Łachacz, A., Głażewski, R., 2015. *Effects of peat drainage on labile organic carbon and water repellency in NE Poland*. Turkish Journal of Agriculture and Forestry, 39: 20–27, DOI: 10.3906/tar-1402-66.
[26] Kondracki, J., 2013. *Regional Geography of Poland*. PWN, Warszawa, 432 p.
[27] Koskinen, M., Minkkinen, K., Ojanen, P., Kämäräinen, M., Laurila, T., Lohila, A., 2014. *Measurements of CO_2 exchange with an automated chamber system throughout the year: challenges in measuring night-time respiration on porous peat soil*. Biogeosciences, 11: 347–363, DOI: 10.5194/bg-11-347-2014.
[28] Krysiak, S., Tołoczko, W., Niewiadomski, A., 2010. *CO_2 respiration in soils of field ecosystems formed from different origin parent material* (in Polish). Ochrona Środowiska i Zasobów Naturalnych, 42: 144–150.
[29] Kutzbach, L., Schneider, J., Sachs, T., Giebels, M., Nykanen, H., Shurpali, N.J., Martikainen, P.J., Alm, J., Wilmking, M., 2007. *CO_2 flux determination by closed-chamber methods can be seriously biased by inappropriate application of linear regression*. Biogeosciences, 4: 1005–1025, DOI: 10.5194/bg-4-1005-2007.
[30] Lafleur, P.M., Roulet, N.T., Admiral, S.W., 2001. *Annual cycle of CO_2 exchange at a bog peatland*. Journal of Geophysical Research, 106(D3): 3071–3081, DOI: 10.1029/2000JD900588.
[31] Lauber-Sauheittl, K., Fuβ, R., Voigt, C., Freibauer, A., 2014. *High CO_2 fluxes from grassland on histic Gleysol along soil carbon and drainage gradients*. Biogeosciences, 11: 749–761, DOI: 10.5194/bg-11-749-2014.
[32] Liang, N., Inoue, G., Fujinuma, Y., 2003. *A multichannel automated chamber system for continuous measurement of forest soil CO_2 efflux*. Tree Physiology, 23: 825–832.
[33] Lindsay, R., 2010. *Peatbogs and carbon: a critical synthesis to inform policy development in oceanic peat bog conservation and restoration in the context of climate change*. RSPB Scotland, 344 p.
[34] Łajczak, A., 2013. *Role of land relief and structure in the formation of peat bogs in mountain areas, as exemplified by the Polish Carpathians*. Landform Analysis, 22: 61–73, DOI: 10.12657/landfana.022.005.
[35] McNeil, P., Waddington, J.M., 2003. *Moisture controls on Sphagnum growth and CO_2 exchange on a cutover bog*. Journal of Applied Ecology, 40: 354–367, DOI: 10.1046/j.1365-2664.2003.00790.x.
[36] Montanarella, L., Jones, R.J.A., Hiederer, R., 2006. *The distribution of peatland in Europe*. Mires and Peat, 1, 1: 1–10.
[37] Moore, T.R., Bubier, J.L., Frolking, S.E., Lafleur, P.M., Roulet, N.T., 2002. *Plant biomass and production and CO_2 exchange in an ombrotrophic bog*. Journal of Ecology, 90: 25–36.
[38] Moore, T.R., Dalva, M., 1993. *The influence of temperature and water table position on carbon dioxide and methane emissions from laboratory columns of peatland soils*. Journal of Soil Science, 44, 4: 651–664, DOI: 10.1111/j.1365-2389.1993.tb02330.x.

[39] Moore, T.R., Knowles, R., 1989.*The influence of water table levels on methane and carbon dioxide emissions from peatland soils*. Canadian Journal of Soil Science, 69, 1: 33–38, DOI: 10.4141/cjss89-004.

[40] Nakano, T., Sawamoto, T., Morishita, T., Inoue, G., Hatano, R., 2004. *A comparison of regression methods for estimating soil-atmosphere diffusion gas fluxes by a closed-chamber technique*. Soil Biology and Biochemistry, 36: 107–113.

[41] Niewiadomski, A., Tołoczko, W., 2016. *Practical aspects of the chamber techniques used in the measurements of exhalation of gases from soil into the atmosphere*, pp. 127–144 (in Polish). In: K. Fortuniak (ed.), Wybrane problemy pomiarów wymiany gazowej pomiędzy powierzchnią ziemi a atmosferą na terenach bagiennych. Katedra Meteorologii i Klimatologii, WNG, University of Lodz, 144 p.

[42] Oleszczuk, R., Brandyk, T., 2008. *The analysis of shrinkage-swelling behaviour of peatmoorsh soil aggregates during drying-wetting cycles*. Agronomy Research, 6, 1: 131–140.

[43] Panikov, N.S., Dedysh, S.N., 2000. *Cold season CH_4 and CO_2 emission from boreal peat bogs (West Siberia): Winter fluxes and thaw activation dynamics*. Global Biogeochemical Cycles, 14, 4: 1071–1080.

[44] Papińska, E., Michalska-Hejduk, D., Niewiadomski, A., Tołoczko, W., 2010. *CO_2 emission from forest and meadow soils on locations of Bolimowski Landscape Park* (in Polish). Ochrona Środowiska i Zasobów Naturalnych, 42: 136–143.

[45] Parkin, T.B., Venterea, R.T., 2010. *Sampling Protocols. Chapter 3. Chamber-Based Trace Gas Flux Measurements*. In: R.F. Follett (ed.), Sampling Protocols: 1–39.

[46] Pawlak, W., Fortuniak, W., Siedlecki, M., Kłysik, K., 2012. *Selected methodological problems of carbon dioxide turbulent exchange measurements on wetland – Biebrza National Park 2010* (in Polish). Przegląd Geofizyczny, 57, 2: 101–111.

[47] Pawlak, W., Fortuniak, K., Siedlecki, M., Zieliński, M., 2016. *Urban – Wetland contrast in turbulent exchange of methane*. Atmospheric Environment, 145: 176–191, DOI: 10.1016/j.atmosenv.2016.09.036.

[48] Raich, J.W., Schlesinger, W.H., 1992. *The global carbon dioxide flux in soil respiration and its relationship to vegetation and climate*. Tellus, 44B: 81–90.

[49] Riederer, M., Serafimovich, A., Foken, T., 2014. *Net ecosystem CO_2 exchange measurements by the closed chamber method and the eddy covariance technique and their dependence on atmospheric conditions*. Atmospheric Measurement Techniques, 7: 1057–1064, DOI: 10.5194/amt-7-1057-2014.

[50] Rochette, P., Hutchinson, G.L., 2005. *Measurement of Soil Respiration in situ: Chamber Techniques*. Published in Micrometeorology in Agricultural Systems. Agronomy Monograph, 47: 247–286.

[51] Schindlbacher, A., Jandl, A., Schindlbacher, S., 2014. *Natural variations in snow cover do not affect the annual soil CO_2 efflux from a mid-elevation temperate forest*. Global Change Biology, 20, 2: 622–632, DOI: 10.1111/gcb.12367.

[52] Schneider, M., Kutzbach, L., Schulz, S., Wilmking, M., 2009. *Overestimation of CO_2 respiration fluxes by the closed chamber method in low-turbulence nighttime conditions*. Journal of Geophysical Research, 114, G03005: 1–10, DOI: 10.1029/2008JG000909.

[53] *Seasonal Bulletin on the climate of the WMO Region VI – Europe and Middle East*, 2014.

[54] Świtoniak, M., Kabała, C., Charzyński, P., 2016. *Proposal of English equivalents for the soil taxa names in the Polish Soils Classification*. Soil Science Annual, 67, 3: 103–116, DOI: 10.1515/ssa-2016-0013.

[55] Tang, X.L., Zhou, G.Y., Liu, S.G., Zhang, D.Q., Liu, S.Z., Li, J., Zhou, C.Y., 2006. *Dependence of soil respiration on soil temperature and soil moisture in successional forests in Southern China*. Journal of Integrative Plant Biology, 48, 6: 654–663, DOI: 10.1111/j.1744-7909.2006.00263.x.

[56] Thomas, K.L., Benstead, J., Davies, K.L., Lloyd, D., 1996. *Role of wetland plants in the diurnal control of CH_4, and CO_2 fluxes in peat*. Soil Biology and Biochemistry, 28, 1: 17–23, DOI: 10.1016/0038-0717(95)00103-4.

[57] Tołoczko, W., Niewiadomski, A., 2010. *Easy way to assay the amount of CO_2 released from soil* (in Polish). Ochrona Środowiska i Zasobów Naturalnych, 42: 151–157.

[58] Tołoczko, W., Niewiadomski, A., 2015. *Measurements of selected greenhouse gases exhalation by using the closed-chamber technique and calculation of hour expiration with regard to CO_2 emissions*. Folia Geographica Physica, 14: 69–74.

[59] Tüfekçioĝlu, A., Küçük, M., 2004. *Soil Respiration in Young and Old Oriental Spruce Stands and in Adjacent Grasslands in Artvin, Turkey*. Turkish Journal of Agriculture and Forestry, 28: 429–434.

[60] Turcu, V.E., Jones, S.B., Or, D., 2005. *Continuous Soil Carbon Dioxide and Oxygen Measurements and Estimation of Gradient-Based Gaseous Flux*. Vadose Zone Journal, 4: 1161–1169, DOI: 10.2136/vzj2004.0164.

[61] Updegraff, K., Pastor, J., Bridgham, S.D., Johnston, C.A., 1995. *Environmental and substrate controls over carbon and nitrogen mineralization in northern wetlands*. Ecological Applications, 5: 151–163.

[62] Urbanova, Z., Picek, T., Tuittila, E-S., 2013. *Sensitivity of carbon gas fluxes to weather variability on pristine, drained and rewetted temperate bogs*. Mires and Peat, 11 (article 4): 1–14.

[63] Vuorinen, M., Kurkela, T., 1993. *Concentration of CO_2 under snow cover and the winter activity of the snow blight fungus Phacidium infestans*. European Journal of Forest Pathology, 23(6–7): 441–447.

[64] Welles, J.M., Demetriades-Shah, T.H., McDermitt, D.K., 2001. *Considerations for measuring ground CO_2 effluxes with chambers*. Chemical Geology, 177(1–2): 3–13, DOI: 10.1016/S0009-2541(00)00388-0.

[65] Wroński, K., 2015. *The dependence of soil CO_2 fluxes on atmospheric conditions during sub-periods of soil respiration*. Forest Research Papers, 76, 2: 129–143, DOI: 10.1515/frp-2015-0013.

[66] Zimov, S.A., Zimova, G.M., Davidov, S.P., Davidova, A.I., Voropaev, Y.V., Voropaeva, Z.V., Prosiannikov, S.F., Prosiannikova, O.V., Semiletova, I.V., Semiletov, I.P., 1993. *Winter bioticactivity and production of CO_2 in Siberian soils. A factor in the greenhouse effect*. Journal of Geophysical Research, 98: 5017–5023.