Disappearance rate of a peatland in Dublany near Lviv (Ukraine) drained in 19th century

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SUMMARY

We aimed to determine the rate of subsidence of a peatland over 133 years since its drainage, and to evaluate the relative contributions of compaction and oxidation to this process. Reliable determination of this proportion is problematic. The results of our calculation were applied to estimate CO_2 emissions by two approaches, assuming different oxidation fractions. The surface of the fen was lowered by 47.9 %, i.e. 2.0 cm year^{-1}, of which about 60 % was due to oxidation and 40 % due to compaction. The process was more intense around a peat mining area, where the surface lowering was greater and the ratio of compaction to oxidation was about 30:70. Our results for the share of oxidation were in line with values most often reported in the literature for warm temperate climate zones. Therefore, the method used for assessing it may be considered reliable.

KEY WORDS: peatland subsidence, disappearance, compaction, oxidation, CO_2 emission

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INTRODUCTION

In drained peatlands the thickness of the peat deposit declines over time. This reduction in peat thickness, due to physical processes and biological oxidation of organic matter, is commonly called peat subsidence (Kasimir-Klemedtsson *et al.* 1997). Peat subsidence involves several mechanisms, three of which are universal: compression (or consolidation) of peat layers below the water table; shrinkage of peat above the water table due to desiccation; and biological oxidation of organic matter in the top layer (e.g. Eggelsmann 1986, Wösten *et al*. 1997, Dawson *et al.* 2010, Couwenberg 2011, Erkens *et al*. 2016). Lowering of the peatland surface and loss of organic matter may be further exacerbated by wind and water erosion, leaching of soluble organic matter, fires and mining (Stephens *et al.* 1984, Berglund & Berglund 2011, Couwenberg 2011, Deverel *et al.* 2016).

The term 'subsidence' means 'to settle' or 'to go down'. Soil subsidence is commonly understood to occur primarily by physical settlement of the soil material. In the case of peat there is also irreversible loss of peat mass due to oxidation. Peat subsidence can, therefore, continue indefinitely. The ultimate result is the disappearance of peatlands from soil maps because they no longer fulfil the mapping criterion (which refers to a minimum peat depth). Thus, ongoing peat subsidence is essentially a process of 'peatland disappearance'.

The rate of peat subsidence depends on many factors, the main ones being peat type, degree of decomposition, bulk density, thickness of the peat deposit, depth of drainage ditches, climate, and land use (e.g. Ilnicki 1967, Roguski 1980, Eggelsmann 1986, Dawson *et al.* 2010, Oleszczuk 2012, Fell *et al*. 2016). Peat subsidence can be divided into two phases. The first phase begins just after drainage, is characteristically rapid, and lasts up to ten (usually 3–5) years. It mainly involves compaction and shrinkage (e.g. Grønlund *et al.* 2008, Ilnicki & Szajdak 2016). The second phase is slower, with oxidation of organic matter as the dominant process (Stephens *et al.* 1984). Oxidation is an irreversible microbiological and chemical process that occurs in the top layer of peat. It results in the release of carbon dioxide (CO_2) and nitrous oxide (N_2O) to the atmosphere (Kasimir-Klemedtsson *et al.* 1997, Czaplak & Dembek 2000). Whereas the methane (CH_4) emissions associated with wet peatlands cease, the emissions of CO_2 and N_2O generally increase. Thus, drainage makes the peatland a significant source of greenhouse gases, especially if it is in agricultural use (Strack 2008, IPCC 2014).

The research literature provides more information on the second phase of peat subsidence. Its course is determined primarily by climate and peat type, and then by physical and chemical properties of the soil and soil moisture content, water table level and land use (e.g. Eggelsmann 1986, Oleszczuk *et al*. 2008). According to Eggelsmann (1986), height loss due to 30 years of oxidation in a cool, humid climate was 30 cm for oligotrophic bogs and up to 60 cm for eutrophic fens; and in a warm climate it exceeded 120 cm. Oxidation is most effective in wood peat, and then in sedge, reed and moss peat (Szymanowski 1997, Oleszczuk *et al*. 2008). It is most intense in summer when the water table is low (Höper 2002). It is fastest during the first years after drainage, and then it slows down. Organic matter loss is usually higher in cropland than in grassland (Ilnicki & Zeitz 2003). Ilnicki (2002) analysed research results from different countries taking into account climatic conditions, drainage intensity, peat type and land use, and found that the annual loss of peatland depth in the second phase was 0.3–1.5 cm for grasslands and 1.5–3.0 cm for arable lands. In Poland, for example, height loss in peat grasslands depends on the depth of drainage and ranges from 0.3 cm for shallow drainage (depth of ditches 0.4–0.6 m) to 1.3 cm for deep drainage (depth of ditches 0.9–1.2 m), while for arable lands it varies between 1.5 and 1.8 cm, *per* year (e.g. Ilnicki 1972, Lipka 1978, Okruszko 1993, Lipka *et al*. 2005, Oleszczuk *et al*. 2008). In The Netherlands, annual subsidence of grasslands on peat ranges from 0.3 cm to 2.2 cm *per* year (Van den Akker *et al*. 2012). In Sweden, peat subsidence after the first phase was shown to depend on the land use and annual peat loss was 0.5 cm for pastures, 1.0 cm for hay meadows, and 1.0–3.0 cm for field crops (Berglund 1989 after Kasimir-Klemedtsson *et al*. 1997, Berglund & Berglund 2010).

To calculate carbon dioxide emissions, a fixed fraction has been used for the contribution of oxidation to peat subsidence (e.g. Armentano & Menges 1986, Oleszczuk *et al*. 2008). However, reliable determination of the oxidative fraction of peat subsidence is problematic, especially when data on soil physical properties are lacking, which is usually the case for long-term datasets.

The aim of the study reported here was to determine the rate of peat subsidence over a period of more than 130 years since drainage and to evaluate the relative roles of compaction and organic matter oxidation in the subsidence process. The results were used to derive carbon dioxide emissions by two independent approaches, assuming different oxidative fractions.

STUDY SITE

The study was conducted at a peatland in Dublany (49° 54′ 53.24″ N, 24° 04′ 22.11″ E), Lviv Province, Ukraine. Ukraine is in the temperate warm climate zone. The investigated peatland is located in the physiogeographical macroregion of the Małe Polesie, on the Volyn-Podolsky Upland. The formation of extensive swampy areas in the Małe Polesie region was facilitated by the flatness of the terrain and thus poor water outflow, the presence of depressions with poor outflow, and wide floodplains in flat river valleys. Peatlands and peat soils occupy a total of 1293.48 km^2, i.e. 15.44 % of this region. At present, almost all peatlands within the Małe Polesie are drained and used for agriculture (Gaskevych & Netsyk 2013). Moreover, peat has been extracted since the nineteenth century. Peat was used mainly for fuel, in agriculture (crop and garden substrate, bedding material), and as a raw material for the chemical industry. In Lviv Province there are 168 peat deposits including more than 20 large peatlands with areas greater than 500 ha, and total peat resources amount to 200,067,000 tonnes (Blazhko & Kiptach 2012). The Dublany peatland, also called Lviv peatland (Gamaliewecke-Grybowecke) (Blazhko & Kiptach 2012, Gaskevych & Netsyk 2013) is located in the Grzybowice-Jarczów valley, which is a glacial lake bottom surrounded by moraine belts. The valley was drained and a Government Channel that connected many transverse ditches was built at its bottom (Bac 1930). The peatland covers an area of 2,226 ha and is classified as deep. Average depth of the peat deposit is about 4.13 m, with a maximum of 6.40 m. Average degree of peat decomposition is 34 %, ash content 14.8 %, and pH 3.36 (Blazhko & Kiptach 2012, Gaskevych & Netsyk 2013).

History of use

A description of drainage works conducted in the Dublany peatland was provided by Bac (1930), who reported that 66 ha of peat grassland was drained in the years 1884–1887 in preparation for the installation of an irrigation (inundation) system. The main drainage ditch for the entire grassland was the regulated Stara Rzeka stream. The flat area was divided into 12 floodplains. The centre of the peatland was crossed by a drainage and irrigation ditch that supplied water from a regulated watercourse, the Nowa Młynówka. The average initial depth of this ditch was 130 cm. In 1905 it was deepened to an average of 160 cm to remedy land subsidence and insufficient drainage. Because this

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action turned out to be ineffective, in 1911 the project was extended with activities aimed mainly at improving drainage of the floodplains. However, it was not implemented due to WWI and as a result "bogging of the peat grasslands increased immeasurably through overgrowth and silting of the ditches and destruction of sluices" (Bac 1930 p. 122). In 1926, only maintenance works involving cleaning of the main drainage ditch (average depth 187 cm) and the Nowa Młynówka were performed. Kornella (1930) mentioned that the peatland in Dublany was exploited from 1887 until about 1930 (authors' note) under management of the manor of the former University of Agriculture, to provide fuel for a distillery. After that time the peat was still intensively mined by local people, mainly for fuel.

Accurate information on the use of the peatland and its drainage status after 1930 is not available to the authors. It may be assumed that it was used in the same manner as most of the Małe Polesie peatlands, which were drained in the 1960s and 1970s and subsequently used as arable land and grassland. However, contrary to expectation, the drainage did not result in improved yields but caused substantial transformation of the peat soils. Commercial peat extraction continued, peaking in the years 1965–1985. Since the 1990s, industrial peat extraction has declined considerably but peat is still mined locally (Gaskevych & Netsyk 2013). For example, the northern part of the research area bordered an area with a regular network of ditches and pits created by peat mining. This area is now partially covered by shrubs, and the water-filled pits are largely overgrown with reed vegetation (*Phragmites australis*, *Typha* sp.). The peat grassland has a high proportion of weed species, notably tufted hairgrass (*Deschampsia ceaspitosa*), and visible turfless spots.

METHODS

Surveying

The research was carried out along two geodetically defined transects (A–B, a–b) in the central part of the Dublany peatland. Geodetic measurements of the peatland surface level were performed in 2015 at 2 cm resolution, with reference to the transect studied by Bac (1930) who used a resolution of 5 cm. Transect A–B runs E–W through the grassland where Bac investigated subsidence of the soil surface in the years 1882–1928, and is about 2,000 m long. This transect was located on the basis of terrain and altitude features found on the maps '*Subsidence of the Dublany peatland - drained grassland*' and '*B. Situational plan*' published by Bac (1930). First, the A–B transect was transformed onto a topographic map, scale 1:10,000 (sheet identification number M-35-73-A-в-2 on the world map from 1985). Then, known geodesic co-ordinates of the sheet grid were used to transform the entire sheet of this map onto the current world map in WGS-84 layout. Thus, the longitudinal profile A–B and the transverse profile a–b (350 m long) could be located on the current interactive geodetic map (Figure 1). Subsequently, the characteristic points of the profile were determined in the field using the Global Navigation Satellite System (GNSS) and a kinematic method, with a Trimble GeoXR6000 receiver.

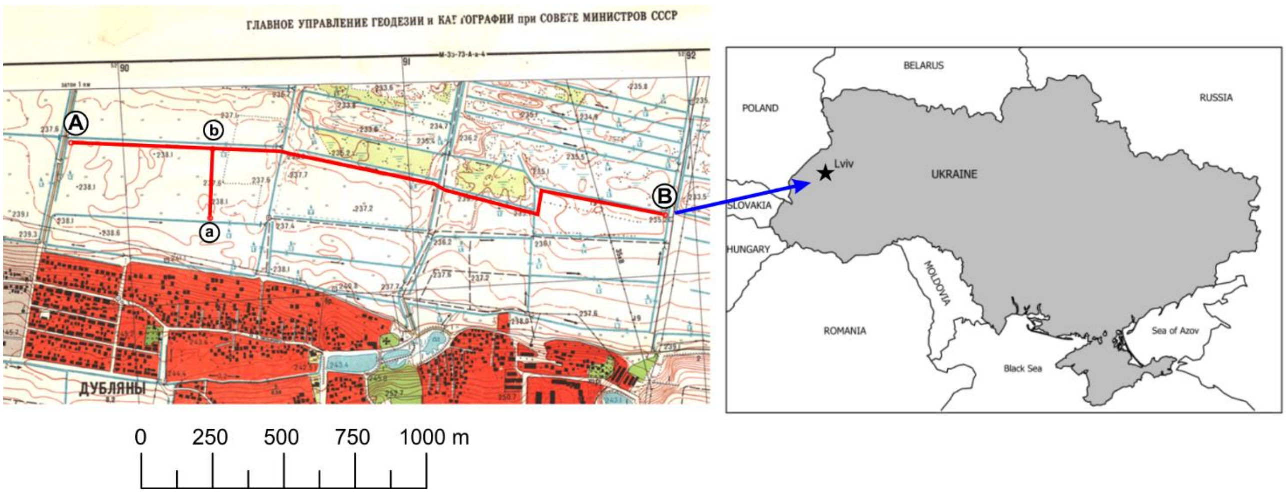


Figure 1. Location of the transects (A–B, a–b) within the peatland in Dublany near Lviv. Source of the map: Central Office of Geodesy and Cartography of the Soviet Union Map Sheet M-35-73-A-в-4 (1991), co-ordinate system 1942.

Peat analysis

Stratigraphic studies along the A–B transect were performed for eight boreholes with depths of 2.8–4.25 m. Peat cores were extracted with an Instorf drill equipped with a 50 cm cylinder. All boreholes reached the mineral substrate. The peat samples, taken from each layer of the cores that was distinguished for botanical composition, degree of decomposition and ash content (n = 62), were subjected to standard laboratory tests (Maksimow 1965, Tobolski 2000, Myślińska 2001). The oven-dry method was applied to determine soil volumetric moisture content and bulk density (samples taken every 20 cm to a depth of 1.4 m). Ash content was determined using a loss on ignition method (550 °C) on samples dried to constant weight. The degree of peat decomposition was determined by a microscopic method (PN-G-04595, Tobolski 2000), and composition of plant remains by a microscopic method using available identification keys (Kac *et al*. 1977, Tobolski 2000, Mauquoy & Van Geel 2007) and comparative slides. To remove humus, the peat was washed through a sieve with a mesh size of 0.2 mm. Each sample was used to prepare three slides that were examined under a microscope at magnification 100–400 times. The types of peat were established on the basis of a genetic classification by Tołpa *et al*. (1967), and the types of gyttja using the classification of Ilnicki (2002).

Determination of peat oxidation and carbon dioxide emission

Subsidence was calculated as described in detail by Lipka (1978) and Lipka *et al*. (1990). We assume that, after the end of peat consolidation immediately following drainage, the peat surface height loss is caused solely by compaction and oxidation above the water table. The proposed method can be used to calculate the shares of height loss due to compaction as a physical component and oxidation as a biochemical component of the phenomenon. The calculation formulae used refer only to compaction and do not consider the oxidative component. The principle of the calculations is presented graphically in Figure 2.

Briefly, the calculations were based on the assumption (Sidiakin 1934) that peat height loss (%) is proportional to the amount of water lost:

$$y = a \cdot X \qquad [1]$$

where y denotes the percentage of height lost, a is an empirical coefficient determined by Sidiakin (1934), and X is water loss (%). The empirical coefficient a which gives the correction for peat height loss after drainage depends on the type of peat (raised bog or fen peat) and its degree of decomposition. For fen peat it was calculated as:

$$a = \frac{1}{1.45 + \frac{28.4}{R}} \qquad [2]$$

where R denotes initial degree of peat decomposition (before drainage). On the basis of our analysis we applied R = 30 % as an average value for peat at depth 1.0–1.5 m (water-saturated layer), giving a = 0.42. Water content was calculated as:

$$X = 100^2 \frac{w_1 - w_2}{w_1(100 - w_2)} \qquad [3]$$

Where w_1 denotes initial peat moisture content (before drainage) (% vol.) and w_2 current peat

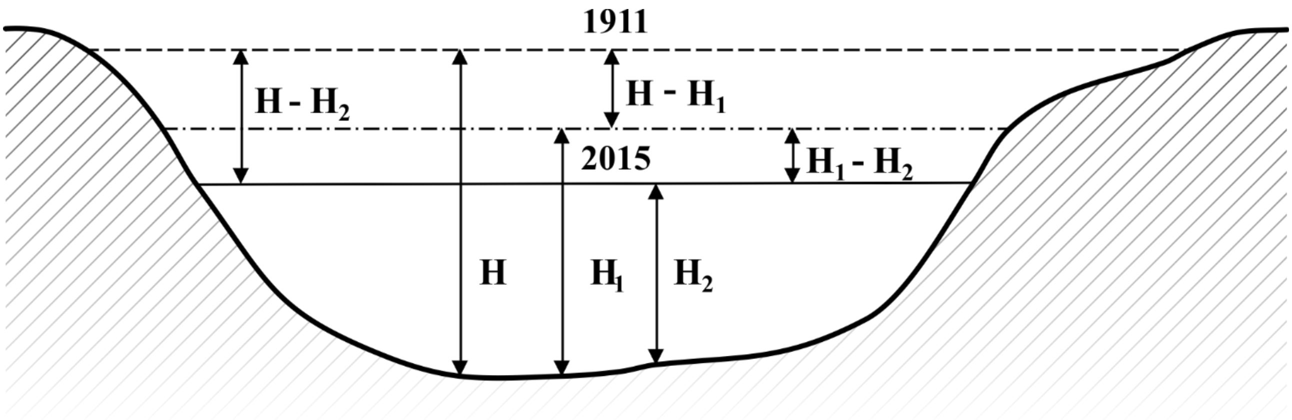


Figure 2. Changes in the surface level of the Dublany peatland in the years 1911–2015 caused by compaction and oxidation. Explanations: H = initial depth of the peat deposit (1882). H_1 = theoretical depth of the current deposit (H_2) if it were not compacted. H_2 = current peat deposit depth (2015). H - H_1 = loss in peat thickness due to oxidation. H_1 - H_2 = loss in peat thickness due to compaction.

moisture content (% vol.). An alternative calculation for peat height loss y is:

$$y = \frac{H_1 - H_2}{H_1} 100 \qquad [4]$$

where H_2 denotes the current depth of the peat layer and H_1 denotes its theoretical depth if it were not compacted (but still without considering oxidation). Rearranging Equation 4 yields:

$$H_1 = \frac{H_2}{1 - y/100} \qquad [5]$$

where y is derived from Equation 1. The difference between H_1 calculated from Equation 5 and the initial peat depth H then yields the oxidative component of peat height loss. This method for determining the shares of compaction and oxidation in peat subsidence based on default values for critical parameters seems acceptable when data are missing and oxidation cannot be computed by other methods (e.g. based on changes in bulk density).

In the next step we wanted to determine whether our calculations of the rate of height loss and the oxidative component used for estimation of carbon loss and CO_2 emissions produce results comparable to those found in the literature for grasslands. We used two different approaches to assess carbon losses and CO_2 emissions associated with subsidence of the Dublany peatland.

In the approach of Van den Akker *et al*. (2008), carbon loss was calculated as the total height loss of the peat deposit multiplied by the volumetric carbon content of the deeper water-saturated layer of peat that had not undergone oxidation. The rationale behind this calculation is that, while oxidation occurs in the drained peat layers near the surface, they are repeatedly deepened to keep the water table at the desired depth. This way fresh, hitherto undrained, deeper peat layers are added to the drained surface layer at a rate that corresponds to height loss. Although these deeper peat layers then undergo compaction as well as oxidation, they can be understood to be completely oxidised over time. A graphical clarification of the method can be found in Couwenberg & Hooijer (2013). The approach of Van den Akker *et al.* (2008, 2012) is accepted by the United Nations Framework Convention on Climate Change (UNFCCC) and used in the periodic reports on carbon dioxide emissions from peat soils used for agriculture in The Netherlands.

Berglund & Berglund (2010) used the volumetric carbon content of the top layer to assess carbon loss and assign a fixed fraction of total subsidence to oxidation. Carbon losses calculated using both of the approaches described are multiplied by 44/12 to convert them to CO_2 fluxes.

All calculations were conducted with reference to the entire A–B transect and to its sections considering different values of soil moisture content and bulk density along the transect (values used for the calculations are given later, in Tables 3 and 4). Also, the calculated carbon loss was used to determine annual water table depth (x) in the Dublany peatland, derived according to the linear regression (y = -14.2x) of Couwenberg & Hooijer (2013).

RESULTS

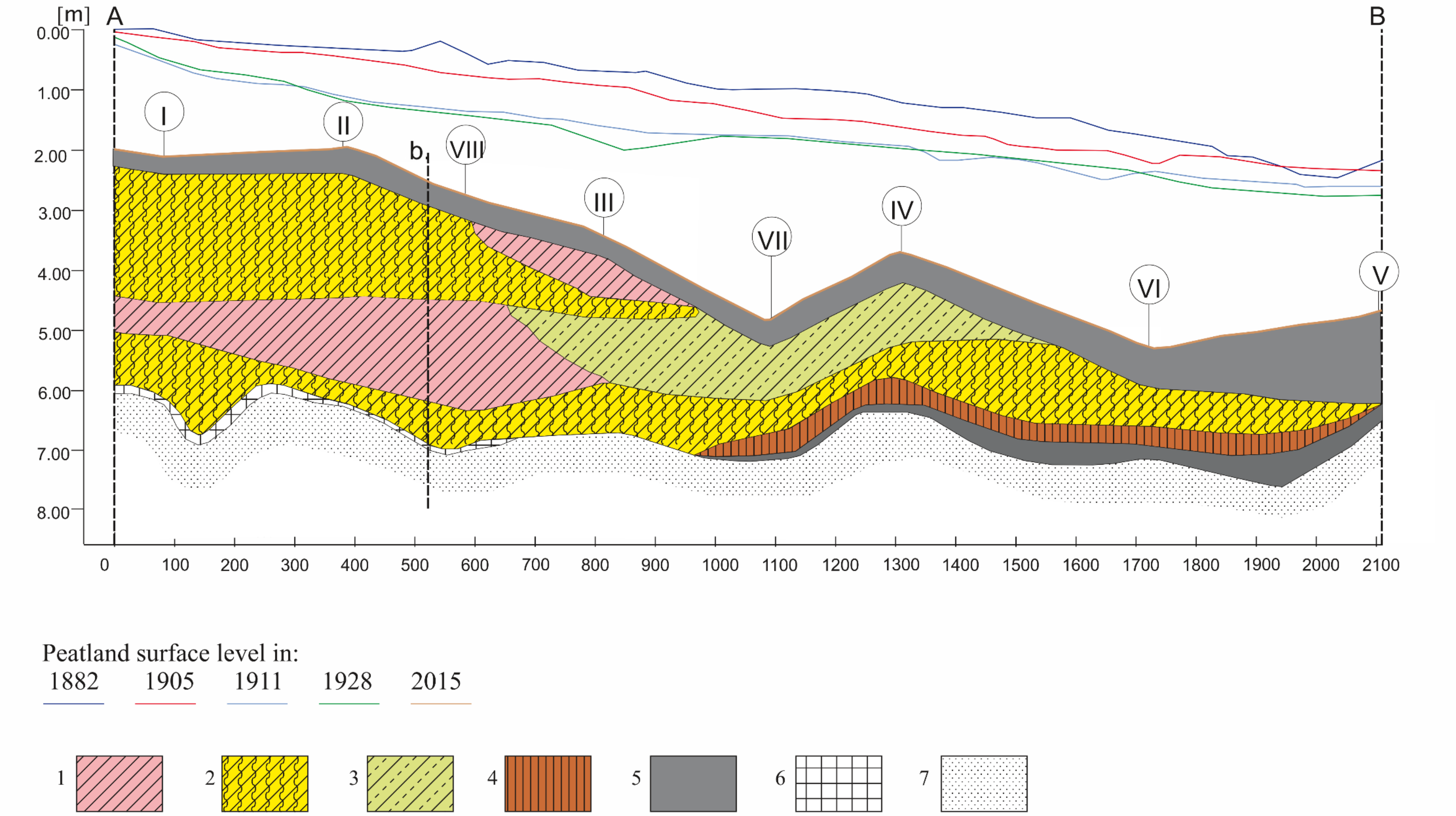
Peat stratigraphy

The stratigraphy of Transects A–B and a–b is shown in Figures 3 and 4. Both the Dublany peatland and its peat deposit are of fen type. The peat is occasionally underlain by a thin layer (0.1–0.25 cm) of mostly calcareous gyttja. The average thickness of peat along the studied transect is 2.7 m and the maximum is 4.25 m. Average ash content (A) is 14.4 % and the average degree of decomposition (R) is 38 %. The dominant peat type is *Cariceto-Phragmiteti* (R = 30–50 %, A = 8.4–24.4 %), accompanied by *Alneti* (R = 45–55 %, A = 18.6–24.2 %), *Cariceti* (R = 35–50 %, A = 9.4–13.1 %) and *Cariceto–Bryaleti* (R = 25–40 %, A = 9.3–9.7 %) peats. The top layer consists of highly decomposed amorphous peat (R > 60 %, A = 14.7–18.3 %) that has been significantly transformed due to moorsh formation.

Degree of disappearance and CO_2 emission

Lowering of the Dublany peatland surface was assessed in the years 1882–1928 by Bac (1930). The part of the peatland with the A–B transect was drained, used as a grassland, and irrigated by means of an inundation system. Bac (1930) measured the peatland surface level four times - in 1882, 1905, 1911 and 1928 - and the last measurement was performed by us in 2015. Changes in the peatland surface level over the years are presented in Figures 3 and 4.

Over 133 years the surface of peat grassland along the investigated A–B transect was lowered, on average, by 271.9 cm or by 47.9 % of the initial thickness of the peat deposit. Mean annual subsidence was 2.0 cm. Height loss along the transverse transect a–b was slightly smaller - on average 220 cm, i.e. 1.7 cm *per* year. However, the subsidence rate was not uniform over the entire study period (1882–2015) (Tables 1 and 2). Over the first 23 years after the first drainage, i.e. in the years1882–1905, average height loss along the A–B



1: *Cariceti* peat; 2: *Cariceto-Phragmiteti* peat; 3: *Cariceto–Bryaleti* peat; 4: *Alneti* peat; 5: amorphous peat (R > 60 %); 6: gyttja; 7: mineral substratum.

Figure 3. Historic height levels and current stratigraphic profile based on peat corings along Transect A–B in the Dublany peatland. I, II… Numbering of boreholes.

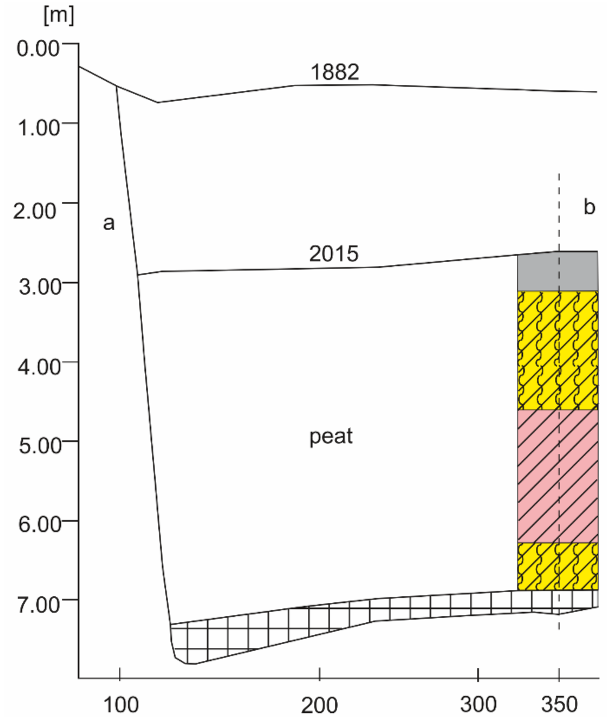


Figure 4. Historic height levels and peat coring along Transect a–b in the Dublany peatland. Legend as for Figure 3.

Table 1. Peat thickness loss in the years 1882–2015 along the A-B transect in Dublany peatland.

Borehole No*	Peat thickness (cm) in the years 1882	1905	1911	1928	2015
I	655	650	605	600	400
II	590	570	510	505	425
VIII	650	610	555	550	410
III	595	570	505	465	325
VII	620	575	540	540	235
IV	520	480	450	445	270
VI	545	500	480	465	185
V	430	420	395	385	180
Mean	575.6	546.9	505.0	494.4	303.8

*numbering of the boreholes as in Figure 3.

Table 2. Peat thickness loss in the investigated time along the A–B transect in Dublany peatland.

	Peat thickness loss (cm) in the years						% of peat thickness loss	
	1882–1905 (23 years)	1905–1911 (6 years)	1911–1928 (17 years)	1928–2015 (87 years)	1882–2015 (133 years)	1911–2015 (104 years)	1882–2015	1911–2015
Entire transect								
Mean	28.8	41.9	10.6	190.6	271.9	201.3	47.9	40.6
AM	1.3	7.0	0.6	2.2	2.0	1.9	0.4	0.4
Boreholes I–VIII*								
Mean	21.7	53.3	5.0	140.0	220.0	145.0	34.6	25.6
AM	0.9	8.9	0.3	1.6	1.7	1.4	0.3	0.2
Boreholes III–V*								
Mean	33.0	35.0	14.0	221.0	303.0	235.0	55.9	49.6
AM	1.4	5.8	0.8	2.5	2.3	2.3	0.4	0.5

*numbering of the boreholes as in Figure 3; AM = annual mean.

transect was 1.3 cm *per* year. Subsidence was greatest in the years 1905–1911, with a mean value of 7.0 cm *per* year. After 1911 it dropped down to 0.6 cm *per* year for the next 17 years. Height loss also varied along the A–B transect. The section located between Boreholes III–V, with its northern border adjacent to the former mining site, subsided on average by 83 cm more than the section between Boreholes I–VIII (Figure 3, Table 2). The annual rate of height loss in the years 1911–2015 was 1.9 cm, which was very close to that between 1882 and 2015 (Table 2).

Based on the rate of surface height lowering, the compaction and oxidative components of peatland subsidence were derived using the method described in the previous section. We conducted our calculations for the years 1911–2015 assuming that consolidation ended a few years after the drainage in 1905. For initial peat moisture content the value of 87.35 % was applied (we assumed that, after drainage, the initial peat moisture content would be 2 % lower than the mean value determined for the water-saturated peat layer, which was 89.35 %). For the current peat moisture content the mean value of 79.35 % was determined. Derived shares of compaction and oxidation for the entire transect in the years 1911–2015 were 43.5 % and 56.5 % respectively. There was little variation in the roles of compaction and oxidation between the transect sections but the proportion of both components, calculated separately for each section, was about 30–70 % (Table 3).

The calculations of carbon dioxide emission were performed for the same study period. Following the approach of Van den Akker *et al*. (2008), carbon loss was calculated using the average rate of subsidence for the period 1911–2015 (0.019 m year^{-1}), a mean peat bulk density of 144 kg m^{-3} for the water-saturated layer of about 1.3 m and assuming organic matter content of 80 % with 55 % carbon by weight (values from Ilnicki 2002). The resulting estimate of annual emission of carbon dioxide for Dublany was 44.1 Mg ha^{-1} or 22.1 Mg CO_2 ha^{-1} year^{-1} *per* cm of peat subsidence.

Following the approach of Berglund & Berglund (2010), carbon loss was calculated by applying the calculated value of 56.5 % to the oxidative component of peat subsidence (0.019 m year^{-1}) and a mean bulk density of 0.259 g cm^{-3} for the top layer of peat and carbon content of 40 % by weight (value according to Maciak 1995). Carbon loss assessed with this approach was 40.8 Mg CO_2 ha^{-1} year^{-1} or 20.0 Mg CO_2 ha^{-1} year^{-1} *per* cm of peat subsidence (Table 4).

Table 3. The share of compaction and oxidation processes in subsidence of the peat grassland at Dublany in the years 1911–2015. Explanations: H = initial depth of the peat deposit (1882 or 1911); H_1 = theoretical depth of the current deposit (H_2) if it were not compacted; H_2 = current peat deposit depth (2015); (H - H_1) = loss of peat thickness due to oxidation; (H_1 - H_2) = loss of peat thickness due to compaction; *numbering of the boreholes as in Figure 3; mean values of initial (w_1) and current (w_2) soil moisture content used for calculations: w_1 = 87.35 %, [1] w_2 = 79.35 %, [2] w_2 = 84.35 %, [3] w_2 = 76.06 %; AM = annual mean.

	Peat thickness			Peat thickness loss					
	H	H_1	H_2	total (H-H_2)		compaction (H_1-H_2)		oxidation (H-H_1)	
	cm	cm	cm	cm	%	cm	%	cm	%
				[1] Entire transect					
Mean	505.0	372.7	303.8	201.3	40.6	69.0	43.5	132.3	56.5
AM	4.9	3.6	2.9	1.9	0.4	0.7	0.4	1.3	0.5
				[2] Boreholes I–VIII*					
Mean	556.7	447.1	411.7	145.0	25.6	35.5	28.1	109.5	71.9
AM	5.4	4.3	4.0	1.4	0.2	0.3	0.3	1.1	0.7
				[3] Boreholes I–VIII*					
Mean	474.0	308.5	239.0	235.0	49.6	69.5	32.2	165.5	67.8
AM	4.6	3.0	2.3	2.3	0.5	0.7	0.3	1.6	0.7

Table 4. Mean peat thickness loss and carbon dioxide emission along the A–B transect in Dublany peatland during the years 1911–2015.

Reference method		Peat thickness loss rate (cm $year^{-1}$)	Oxidative component (%)	CO_2 emission (Mg ha^{-1} $year^{-1}$)*	Water table** (m below ground level)
Van den Akker *et al*. (2008)	entire transect	1.9	-	44.1 [1]	0.85
	Boreholes I–VIII***	1.4	-	33.0 [2]	0.63
	Boreholes III–V***	2.3	-	52.7 [3]	1.00
Berglund & Berglund (2010)	Entire transect	1.9	56.5	40.8 [4]	0.78
	Boreholes I–VIII***	1.4	71.9	37.2 [5]	0.71
	Boreholes III–V***	2.3	67.8	59.9 [6]	1.15

*soil bulk density in g cm^{-3} used for calculation: [1] 0.144, [2] 0.146, [3] 0.142, [4] 0.259, [5] 0.254, [6] 0.262; **annual water table depth x (m) derived basing on carbon loss (Mg ha^{-1} $year^{-1}$) from the equation y = –14.2x according to Couwenberg & Hooijer (2013); ***numbering of boreholes as in Figure 3.

Carbon loss varied along the A–B transect. Calculations show that the average share of oxidation in the section comprising grasslands between Boreholes I–VIII and in the section between Boreholes III–V adjacent to the former mining site were comparable (about 70 %), but the surface height loss was higher by 0.9 cm *per* year in the second section (Table 4). It was reflected in carbon dioxide emissions, which were estimated by the two approaches at, on average, 35 Mg CO_2 ha^{-1} $year^{-1}$ for the grasslands and 57 Mg CO_2 ha^{-1} $year^{-1}$ in the grassland section adjacent to the former mining site (average values from calculations using the methods of Van den Akker *et al.* 2008 and Berglund & Berglund 2010; Table 4). An annual mean water table depth corresponding to the carbon flux rates calculated by the two approaches (Couwenberg & Hooijer 2013) were on average 0.67 m for the first and 1.08 m for the second of the analysed sections of the grassland (Table 4).

DISCUSSION

The rate of subsidence in the Dublany peatland was not uniform over the years 1882–2015 and depended mainly on the efficiency of the drainage system. In 1884, the depth of the main drainage ditch turned out to be insufficient to allow the outflow of water from inundated meadow and it triggered a rise of surface level in the area of the ditch mouth, which was noticed by Bac (1930). A significant loss of peat thickness resulted in deepening of the main drainage ditch in 1905 to improve drainage efficiency. It can be assumed that the first phase of peatland subsidence, which is mainly consolidation of the peat below the water table, ended around 1911. After that year no drainage activities were performed within the peatland due to WWI, and this increased the area of waterlogging and considerably reduced the rate of peat loss. Again, it resulted in peat swelling and rising of the peatland surface in some locations. The first surface level measurement after WWI was carried out in 1928, and there were no subsequent measurements until 2015. The subsidence rate over these 87 years was probably not uniform, but considerably accelerated in the years following WWII, when peat adjacent to the investigated area was mined industrially and by local inhabitants. However, there are no measurements that could confirm variability in the rate of peatland disappearance within this period. Nevertheless, there were noticeable differences in the decline of the peatland surface along Transect A–B. The rate of surface height loss was generally greater (after the years 1905–1911) in the section of peat grassland adjacent to the former peat mining site and along the transect up to the main ditch, and so the depth of highly decomposed peat was increasing (degree of decomposition in the upper layer increased from 65 % to 85 %) (Figure 3). This indicates that, sometime after 1928, the water table in this area was lowered (probably due to peat extraction after WWII) and the rate of surface decrease could result mostly from consolidation of peat at greater depth.

The degree and rate of peatland subsidence depends on many factors. In general, research studies have shown that the deeper the drainage, the greater the peat thickness, and the lower the bulk density, the more dynamic the process will be (see Ilnicki & Szajdak 2016). Mean annual values reported by various authors vary widely, and for central Europe they range from 0.3 to 3.0 cm $year^{-1}$ (Kasimir-Klemedtsson *et al.* 1997, Jurczuk 2000, Ilnicki & Szajdak 2016). The majority of observations cover about 30 years following drainage, i.e. a much shorter period than in this study. The disappearance of peat under grassland in Dublany over 133 years closely resembled the process described by Łyszczarz & Suś (2009) for grassland in the Bydgoszcz Channel valley. There, the decrease in peatland thickness over 90 years ranged from a dozen or so to more than 250 cm and was generally larger closer to the main watercourse. The mean annual decrease in surface height was around 2 cm. More intense disappearance was reported for the Holme Post peatland in Great Britain (Hutchinson 1980), where the total decrease in land level was about four metres over 130 years, of which nearly two metres occurred in the first decade after draining. This reflected a total annual height loss of around 3 cm, with a rate of 20 cm *per* year for the first 10 years and 1.7 cm *per* year over the following years.

In general, the rate of peatland height loss clearly differs between the first and second phases. Various authors have reported that the peatland surface level may be lowered by 5–10 cm *per* year during the first phase after drainage (see Oleszczuk *et al.* 2008 for a review). Lowering of the Dublany peatland surface between 1882 and 1911 (7.0 cm $year^{-1}$) fitted well within the quoted range. Eggelsmann (1986) reported that height loss was most rapid after the first drainage and amounted to 0.5–3 m. Each successive drainage performed in long-term management of peatlands caused their further subsidence, but rates were slower and reached 10–50 cm over 30 years. Ostromęcki (1956) investigated subsidence of a peatland in Sarny (Polesie region) and found that the surface level was lowered by 78 cm 22 years after drainage, with an initial depth of the peat deposit 5.23 m and a drainage depth of 0.9 m. The mean depth of the Dublany peat deposit was 5.76 m and it declined by 28.8 cm over 23 years, i.e. significantly less rapidly than reported by Ostromęcki (1956), probably due to low efficiency of the first drainage. When the efficiency of drainage was improved, lowering of the peatland surface level accelerated and reached 41.9 cm over the next six years. Over 29 years, the total decline in surface level of the Dublany peatland equalled 70.7 cm. As suggested by Bac (1930), the degree of lowering was also affected by inundation of the grasslands, which supplied sediments to the area and enriched the soil with oxygen, which could also accelerate peat mass oxidation.

Ilnicki (1972) claimed that peatland surface lowering in the second phase depended primarily on the depth of drainage of the peat body, and to a smaller extent on the peat type and land use, particularly in the case of grasslands. Similar conclusions were reached by Mundel (1976), who described a much greater effect of water level and soil temperature than of land use on the intensity of oxidation. Variable drainage intensity may explain differences in surface lowering along the A–B transect at Dublany which, especially in the years 1928–2015, was greater near the area of peat extraction. Moreover, the stratigraphic structure of the peatland changes at about 650 m along Transect A–B (Figure 3). The peat of *Caricato-Phragmiteti* and *Alneti* types occurring up to 650 m are joined at this point by the *Cariceto-Bryaleti* type, which might have affected the degree of subsidence. The decrease in peatland surface level observed by Ostromęcki (1956) was considerably greater when the deposit contained poorly decomposed moss and moss-reed peat with low ash content and high moisture content, as compared to the highly decomposed alder and other peat with high ash content and bulk density deposited in the valley.

It is difficult to reliably determine the share of organic matter compaction and oxidation in peat subsidence, and the data provided in the literature are often discordant. In the case of the Dublany peatland we established the ratio of compaction to oxidation in the years 1991–2015 to be about 40:60 for the entire investigated transect, which corresponded to oxidative peat loss of 1.3 cm $year^{-1}$. However, when mean values of bulk density for each analysed section of the transect were used as input data for calculations, the compaction:oxidation ratio changed to about 30:70 and peat loss rate due to oxidation for the grassland ranged from 1.1 to 1.6 cm $year^{-1}$ (higher rate for the grassland section adjacent to mining site). Our findings match the reported values. According to various authors (see Berglund & Berglund 2011 for a review), drained peat soils in agricultural use disappear as a result of oxidation at a rate of 0.2–2.2 cm $year^{-1}$. In Poland, Okruszko (1991) found that oxidation was responsible for 77.2 % of the subsidence of peatland in the Biebrza valley. In contrast, Jurczuk (2000) reported a range of 20–50 %, depending on soil type. A study conducted in The Netherlands showed that peat subsidence was 52 % due to biological oxidation of peat (Schothorst 1977 in Deverel *et al.* 2016). In Sweden, oxidation was assumed to be responsible for 35 % of peat subsidence on average (Berglund & Berglund 2010). In general, the literature values for peat subsidence due to oxidation after the consolidation phase vary from a few to nearly 100 % (Kasimir-Klemedtsson *et al.* 1997). Also, the rate of oxidation is highly seasonal and varies with soil moisture content and temperature (Kechavarzi *et al.* 2007). Nevertheless, for drained peat soils in agricultural use these values usually range from 70 to 80 % (Oleszczuk *et al.* 2008, Couwenberg & Hooijer 2013).

Carbon dioxide emission from organic soils may be assessed using three methods: estimation based on disappearance rate, models based on input data such as precipitation and temperature, and direct measurements. According to Kasimir-Klemedtsson *et al*. (1997) and Couwenberg & Hooijer (2013), the first and third methods yield similar results. Our calculations of carbon dioxide emission from Dublany peatland following the approaches of Van den Akker *et al.* (2008) and Berglund & Berglund (2010) gave different values. The estimates following Van den Akker *et al.* (2008) were about 7 % higher than the estimates by Berglund & Berglund (2010) for the entire transect and about 10 % lower for the two sections separately. These differences are due to changes in oxidative component used for the second calculation method. The estimate of annual emission of carbon dioxide from the entire transect (on average 21.2 Mg CO_2 ha^{-1} year^{-1}), computed using the same methods, concurred with the outcomes provided by Van den Akker *et al.* (2008, 2012) who found that one centimetre of peatland disappearance was associated with CO_2 emissions of about 22 Mg CO_2 ha^{-1} year^{-1}. In general, along the transect, carbon dioxide emission was 38 % higher in the section of grassland adjacent to the former peat extraction site. A greater rate of height loss, higher degree of peat decomposition (70–85 %) and deeper layer of amorphous peat in this section (Figure 3) indicate that drainage was more intense. Wösten *et al.* (1997) estimated the additional subsidence due to deep water table close to the drainage channels to be 30 %. Considering that mining sites are usually deeply drained, higher carbon flux as the effect of low annual mean water table (depth 1.1 m) as observed by Couwenberg & Hooijer (2013) may be legitimated. Various studies (Turbiak 2006, Kluge *et al.* 2008, see Berglund & Berglund 2011, Hooijer *et al.* 2012, Couwenberg & Hooijer 2013) have indicated that carbon dioxide emissions increase linearly with water table depth. A derived annual mean water table depth in Dublany of about 0.81 m (average value from calculations using the methods of Van den Akker *et al.* 2008 and Berglund & Berglund 2010) was within the range reported by Bac (1937) for the 1930s, when it fluctuated between 0.6 and 1.1 m in summer.

The Intergovernmental Panel on Climate Change (IPCC 2014) employs emission factors that are defined by climate zone and land use type. For grassland in the warm temperate zone the default emission factor is 5.3 Mg C ha^{-1} year^{-1} (i.e. 19.6 Mg CO_2 ha^{-1} year^{-1}) for drained soils with low nutrient content, 6.1 Mg C ha^{-1} year^{-1} (i.e. 22.6 Mg CO_2 ha^{-1} year^{-1}) for deep-drained soils rich in nutrients, and 3.6 Mg C ha^{-1} year^{-1} (i.e. 13.3 Mg CO_2 ha^{-1} year^{-1}) for shallow-drained soils. Carbon dioxide emissions from the Dublany peat grassland were about twice as high as the value for deeply drained soils rich in nutrients. The calculated high carbon dioxide fluxes and the difference in estimations by the two approaches are probably due to the fact that another ‘consolidation phase’ occurred after WWII. We could not exclude it from the annual height loss and oxidative component calculations due to the lack of surface level measurements between 1928 and 2015. Also, it cannot be completely ruled out that a layer of peat was extracted from that part of investigated area. If this is indeed the case, the surface lowering due to drainage would be smaller than we assumed.

Transition between the stages of peatland disappearance (consolidation, compaction and oxidation) occurs gradually (Wösten *et al.* 1997) and it is difficult to define clear borders between them. However, the estimated ~ 70 % share of oxidation in peatland disappearance was consistent with values reported in the literature for the temperate warm climate zone. The calculation procedure for assessing the roles of oxidation and compaction presented in this paper was first applied at two fens in Poland by Lipka (1978) and Lipka *et al.* (1990). For the first site (89 years) the ratio of compaction to oxidation was 21:79, while for the second one (96 years) it was 35:65. Therefore, the method used to calculate these components of peatland subsidence may be considered reliable.

However, it should be emphasised that long-term studies on the degree and rate of peat subsidence provide only estimated results, as the measurements are usually conducted at small scale and the process is affected by numerous factors of variable nature and intensity (e.g. whole-catchment hydrological changes, changes in land use), and accurate data are often unavailable.

Restricting peat oxidation is important not only to reduce greenhouse gas emissions but also to limit the loss of productive land through soil degradation and peatland disappearance in times of rising sea levels (Hoogland *et al.* 2012, Joosten *et al.* 2012). In this context, rational use of peatlands is recommended.

This should be executed mainly by abandoning the practices of draining natural peatlands and using them as arable land, and instead converting them into meadows and pastures, raising water levels, or adjusting existing drainage systems to perform both drainage and sub-irrigation functions for land in agricultural use (Oleszczuk 2012). Carbon loss from degraded peatlands may be considerably reduced only by rewetting. On such ground, paludiculture may be introduced as an alternative form of sustainable utilisation (Wichtmann *et al*. 2016).

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