Accumulation and emission of carbon by peatlands, including alkaline fens.

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Introduction

Peatlands cover ca. 3,7 million km^2 = ca. 2,5% of the Earth's land, gathering approx. 25 – 30% of the resources of carbon accumulated in the ecosystems (Ilnicki 2002, Oleszczuk 2012), which corresponds to an estimate of 60 – 75% of carbon resources in the atmosphere and twice the carbon resources accumulated through forests. Live peatlands accumulate carbon resources by accumulating biomass in the form of peat. The degradation of peatlands, i.e. its drainage, causes peat's decomposition and decay as well as the release of carbon dioxide. On a general level it is thus quite obvious that the accumulation and emission of carbon from peatlands is significant for the global carbon balance. In order to prevent the emission of CO_2 to the atmosphere it is essential to prevent the release of carbon accumulated in already existing peatlands as well as to capture and accumulate by peatlands the carbon from the atmosphere in the future.

According to Wetlands International estimations, the global CO_2 emission from degraded peatlands worldwide is approx.2×10^9 tones per year (in other sources one may encounter the estimations of 1.3 – 5×10^9 tons per year, however, there is a consensus regarding the magnitude), with a growth trend by ca. 2% per year. The area of degraded and requiring restoration peatlands is estimated as at least 0,5 million km^2. Emission of the carbon dioxide from anthropogenically degraded peatlands is estimated as ca. 5-6% of the total anthropogenic emission of this gas and ca. 30% of the emission resulting from the land use and land-use related changes. Natural emissions are not included within these estimations.

The area of fens in Poland is estimated to be 1211 thousand ha. (=12,11 thousand km^2). Czaplak and Dembek (2000) estimated that of approx. 817 thousand ha of peatlands used as grasslands the emission that occurs annually is of 14,5 million tons of CO_2 which is equal to ca. 4% of the Polish annual emission of carbon dioxide from the combustion of fossil fuel. Jurczuk (2012) estimates the current emission of the carbon dioxide from Polish peatlands meliorated for the agricultural use as 6,7 Mt which would constitute 2% of the emission of the combustion of fossil fuels. Nevertheless, these calculations do not take into account other types of fens, i.e. forested peatlands. Joosten (2010), on the basis of the areas of forested and agriculturally used peatlands and average emission factors, estimates the annual CO_2 emission from degraded peatlands in Poland as 25,8 million tons, or as 7,5% in comparison to the emission from the combustion of fossil fuels. This would place Poland in a group of 10 world's biggest emitters of CO_2 from the degraded peatlands' areas.

In certain countries the role of fens in the greenhouse gases balance, and consequently, in preventing climate changes, is generally strongly emphasized. For example, in strongly peatlands covered Scotland protecting and reconstructing peatlands is thought to be an essential action that prevents climate changes. There are attempts of taking that aspect into consideration in terms of assessing the impact of certain actions on the environment.

Sometimes it significantly alters the evaluation of, i.e. the impact of wind farms on the environment; located on “useless” bogged areas they turn out to be “net emitters” of the carbon dioxide because the estimated CO_2 emission that stems from degradation of peatlands connected with construction of windmills appears to be bigger than emission savings in the production of wind energy, rather than from burning coal (Madsen and Ebmeier 2012 and works there cited). It is also estimated how the restoration of peatlands may affect the carbon balance (i.e. Artz and others 2012 assume that it is effect between 0,6 and 8,3 tons of CO_2 equivalent per hectare of reconstituted peatlands annually).

In reality, however, the mechanism of interactions between fens and their condition and the balance of so called greenhouse gases and, consequently, possible climate changes are not as simple as it is often assumed. In particular::

- The carbon balance of a specific fen is individual and highly dependent on the ecohydrology of an individual object (et. Worall et al. 2011). It is very doubtful whether averaged estimates derived from studies carried on random peatlands, and this is the only available kind of scientific data, may be the basis of such generalized estimates. It is rather certain that they cannot be referred to objects other than those which were surveyed, and it is certain that basing on the “standard, averaged parameters” there is no possibility, even a rough one, of estimating the emission/capture of the carbon dioxide for a particular peatland.
- Carbon dioxide emitted from peatlands occurs not only directly, but also indirectly: by leaching of organic components and so called dissolved carbon substances which decompose into carbon dioxide in streams and other waters beyond the peatland. Those mechanisms are poorly known, even though their role may be more important than the role of the direct emission.
- Apart from the participation in the carbon cycle, peatlands emit methane and nitrous oxide which are also classified as greenhouse gases and, in addition, their impact on the climate is estimated respectively as 20-25 and 300-350 more powerful than carbon dioxide. The methane emission processes are typical for natural, well-hydrated peatlands and, unlike the carbon dioxide emission, are inhibited on over-dried and degraded peatlands.
- The mechanisms responsible for the emission of greenhouse gases and the carbon sequestration by peatlands’ ecosystems are definitely non-linear, which means that to a large extent they have the nature of a “switch off” system, i.e. associated with starting and stopping the biochemical activity of enzymes or with other, not known yet mechanisms (i.e. Fenner & Freeman 2011). It means that the use of linear mathematical models used for estimating emission from peatlands is, in general, methodically incorrect.
- Undoubtedly, there may exist feedbacks between climate changes (warming, local cooling, the increase in the frequency and the depth of dry periods, or even a direct increase of the concentration of carbon dioxide) and the carbon accumulation in

peatlands, but we do not have the knowledge about them and most likely we will not have one other than post factum. There also exist some theories, supported by scientific data, that climate changes will cause a sharp increase of the emission of greenhouse gases from peatlands (a positive feedback; cf. i.e. Freeman, Ostlen, Kang 2001, Fenner & Freeman 2011), as well as that the climate warming may increase carbon capture from the atmosphere by peatlands (cf. i.e. Blodau, Siems & Beer 2011, Charman & others 2013). In reality, the exact character of expected climate changes is not even known and predicting how they may affect the functioning of peatlands' geosystems is very doubtful.

Even if we assume that peatlands in a natural state are practically absorbers of greenhouse gases whereas degraded fens are their emitters, it does not necessarily mean that the renaturalization of fens will positively influence the balance of those gases. The concept of renaturalization of peatlands is mostly understood as their rehydration. However, ecologic systems created this way are not and will never be identical with an untouched peatland. The knowledge of the emission and the absorption of carbon dioxide, methane and nitrous oxide cannot be exploited in terms of renaturalized peatland. Actual data referring to emission and absorption of greenhouse gases by rehydrated peatlands are very limited, and the results are not obvious (i.e. Beyer & Hoper, 2014)..

Attempts and declarations of peatlands' inclusion in greenhouse gases balances

Despite the aforementioned methodical doubts, postulates for peatlands' inclusion in global and national greenhouse gas balances, and eventually in emissions trading schemes, have been formulated for several years. First guidelines about how this inclusion should be carried out formed part of the guide of the International Climate Panel to create national greenhouse gases balance from 2006 (IPCC 2006). Subsequently, the suggested emission factors were the topic of a discussion for several years (check Couwenberg 2009).

During the climate conference in Durban (2011) the declaration (decision 2/CMP.7) concerning the possibility of inclusion of greenhouse gases emission resulting from land-use, changes of land-use and forestry to national emission balances was accepted. In balances, the anthropogenic emission is, as a standard, taken into consideration, which comes from exploited peatlands. However, emissions from natural and unmanaged peatlands are omitted. In the autumn of 2013 the Wetlands Supplement (IPCC 2013) to the methodic guidelines of the International Climate Panel, referring to estimating the emission coming from those sources, was published.

The current guidelines (IPCC 2013) recommend as a primary estimation method (so called Tier 1 – level 1) the adoption of typical factors of emission from drained organic soils depending on the land-use type. The factors assume that the purpose of including greenhouse gases into national balances are anthropogenic emissions; that is why they do not estimate emissions from natural peatlands. Standard factors collected in the guidelines are presented in "tons of carbon included in the carbon dioxide emitted anthropogenically from a hectare per year" (t CO_2-C), which may be converted into tons of carbon dioxide thanks to 3.67 ratio, and, for instance, may amount to:

Category of area	Standard factor of emission of tons of CO_2-C/ha per year (average and 95% confidence interval)	Standard factor of emission of tons of CO_2/ha per year (average)
Forests in depleted locations of dehydrated peatlands of the boreal zone	0,25 (-0,23-0,73)	0,91
Forests in fertile locations of drained peatlands of the boreal zone	0,93 (0,54-1,3)	3,41
Forests on dehydrates peatlands of the temperate zone	2,6 (2,0-3,3)	9,54

Agricultural crops on drained peatlands of boreal and temperate zones	7,9 (6,5-9,4)	28,99
Grasslands on drained peatlands of the boreal zone	5,7 (2,9-8,6)	20,91
Grasslands on depleted and drained peatlands of the temperate zone	5,3 (3,7-6,9)	19,45
Grasslands on fertile, shallow-drained peatlands of the temperate zone	3,6 (1,8-5,4)	13,21
Grasslands on fertile, deeply drained peatlands of the temperate zone	6,1 (5,0-7,3)	22,39
Peatlands that are drained with the objective of exploitation (not including the emission from the exploited peat) of boreal and temperate zones	2,8 (1,1-4,2)	10,28

These factors were gathered basing on scientific works containing appropriate estimations. Examples of such work were discussed further.

Alkaline fens in greenhouse gases emission and absorption estimations

There are virtually no results of carbon dioxide or any other greenhouse gases emission measurements which specifically and unambiguously could relate to alkaline fens, namely the 7230 Natura 2000 habitat. Within areas with continental climate, the natural fens are characterized by the faster growth of the peat bed and by more intensive sequestration (accumulation) of carbon than bogs. On the other hand, they are converted into grasslands more often than bogs, which means bogs' degradation. However, there is no data that would allow distinguishing alkaline fens from other types of peatlands in terms of their contribution to the carbon balance. Theoretically, the role of this specific type of fens may be special, since carbon is being accumulated not only as peat, but also as carbon precipitates that are deposited in fens (travertine deposits); nevertheless, this issue is still not covered by any quantitative analysis.

Some of the fens examined in respect of the carbon balance, mentioned in this analysis, were drained "post-moss" fens. However, descriptions of research subjects do not enable a precise diagnosis in this respect.

Estimations of the carbon balance in peatlands in Europe and worldwide

There have been numerous attempts of determining the carbon dioxide emission from natural and degraded peatlands in many places around the world. An overview of the results obtained so far in Europe was compiled by Byrne et. al.(2004), Couwenberg (2009), Jassens et. al. (2005) and Lindroth et. al. (2007), followed up with complementing publications by Klimkowska (2008). Examplary data are given below:

Location	Type of the fen	An emission of tons of CO_2/ha per year (=3,67 x tons C/ha per year) Negative values signify an accumulation of CO_2	Source (specific source data can be found in Klimkowska's publication from 2008).
Europe	Natural peatlands	-1,28	Janssens i in. 2005
Finland	Fens	-2,93 do -7,34	Lindroth et al. 2007
Finland	Fen	-2,06	Aurela et al. 2007
Sweden	Deprived sedge fens	-2,01	Sagerfors et al. 2008
Netherlands	Remarshed grassland on peat	-11,34	Hendriks et al. 2007
Netherlands	Semi-natural grassland on deprived soak-way fens.	-5,32	Jacobs et al. 2007
Netherlands	Meadow mown twice on fen	15,56	Veenendaal et al. 2007
Netherlands	Intensively utilized, fertilized meadow on peat	4,04	Jacobs et al. 2007
Great Britain	Moist, extensive meadow on fen	2,16	Lloyd 2006
Netherlands	Meadow on peat for the intensive milk production	15,52	Veenendaal et al. 2007
Europe	Drained fens (meadows and forests) - average	4,40	Jassens i in. 2005
Netherlands	Molinia meadow on degraded, drained fen	6,60	Jacobs et al. 2007
Netherlands	Meadow on fen	8,07	Jacobs et al. 2007
Great Britain	Meadow on fen	20,18	Bellamy et al. 2005
Europe	Arable land on degraded peatland.	24,22	Jassens i in. 2005

Similar compilation was also made by Oleszczuk (2012):

Emission from bogs
(specific source data can be found in Oleszczuk's publication from 2012)

Localization	Type of use	Water table (m)	Liming Fertilizing	CO_2 emission (t · ha^{-1}·$year^{-1}$)	Source
Identification on the basis of the subsidence of peat soils					
NW Germany	Arable soil	drained	limed fertilized	16,1	Eggelsmanni Bartels, [1975], Höperi Blankenburg [2000]
NW Germany	meadow	drained	limed fertilized	17,7	Kunze [1992]
Sweden	meadow	drained		12,8	Hillebrand [1993]
Direct measurements under field conditions					
S Germany	meadow	drained (50 years) annual average: 0,29 variations: 0,54	-	16,2 ±2,6	Drösler [2005]
S Germany	meadow	Drained (50 years)	-	9,0 ±1,7	Drösler [2005]
Russia	meadow	drained	-	20,0	Krestapova i Maslov [2004]

Emmision from peatlands
(Specific source data can be found in Oleszczuk's publication from 2012):

Localization	Type of use	Water table (m)	Liming Fertilizing	CO_2 emission (t · ha^{-1}·$year^{-1}$)	Source
Direct measurements in lysimeters, soil not covered with plants					
NE Germany		0,3	-	10,5 – 14,3	Mundel [1976]

NE Germany NE Germany		0,6 0,9-1,2	- -	14,6 – 20,6 13,7 – 24,5	Mundel [1976] Mundel [1976]
Identification on the basis of the subsidence of soil					
Poland (Biebrza) NW Germany S Germany Sweden Sweden	arable soil arable soil arable soil arable soil, grain arable soil, grain	0,7 – 0,9 0,8 – 1,8 drained drained drained	fertilized fertilized fertilized - -	41,1 39,9 – 60,5 24,2 – 36,3 31,0 – 62,0 62,0 – 92,0	Okruszko [1989] Eggelsmanni Bartels [1975] Schuch [1977] Kasimir – Klemedtssoni in. [1997] Kasimir – Klemedtssoni in. [1997]
Poland (Biebrza) Poland NE Germany S Germany Netherlands Netherlands Sweden	meadow meadow meadow meadow meadow meadow meadow	0,5 – 0,7 - drained summer: 1,0 – 2,0 0,7 – 1,0 - -	fertilized - - fertilized fertilized - -	31,5 10,0 – 18,0 24,2 16,9 14,1 – 16,9 8,0 – 30,0 15,0 – 30,0	Okruszko [1989] Czaplak i Dembek [2000] Lorenz i in. [1992] Weinzierl [1997] Schothorst [1976] Kasimir – Klemedtssoni in. [1997] Kasimir – Klemedtssoni in. [1997]
Direct measurements under field conditions, soil not covered with plants					

Canada Canada	Arable soil meadow	0,2 – 0,9 >0,5	- -	5,9 – 6,4 7,0	Glenn i in. [1993] Glenn i in. [1993]
Finland NW Germany NW Germany	meadow irrigated meadow meadow	0,2 – 1,2 winter: 0,1-0,4 summer:0,5 winter: 0,3-0,5 summer: 0,6	fertilized, limed - -	14,4 – 14,7 14,1 – 17,6 15,1	Nykäneni in. [1995] Meyer i in. [2001] Meyer i in. [2001]

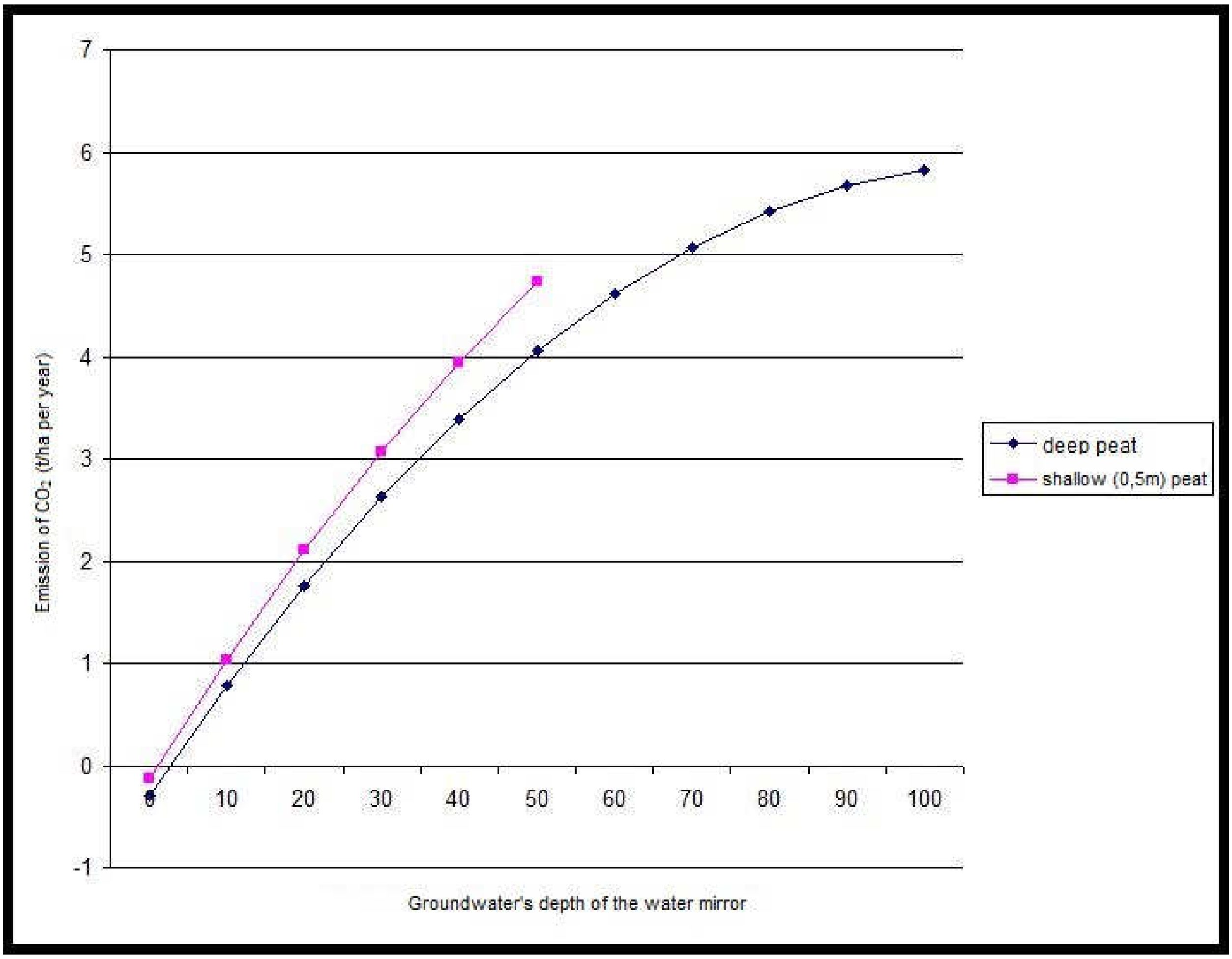
Values differ from those reported usually in other sources in relation to the magnitude of the estimation (Păcurar et al. 2010 – CO_2 emission from peatlands of more than 600 t/ha per year).

Oleszczuk (2012) compiled also empirical equations for estimating the emission of $CO_2$from drained fens that were suggested by other authors (Specific source data can be found in Oleszczuk's publication from 2012):

Description of the peat soil	Empirical equation	Sources
	Soil temperature	
Shallow peat bed (to 0,5m)	$y = -0,076 + 0,3371x$	
Deep peat bed (>0,5m)	$y = 0,860 + 0,4542x$ where: y – CO_2 emission [$g \cdot d^{-1}$] x – soil temp. on the depth of 10cm [^oC]	Mundel [1976]
Peat-muck	$y = 0,198x + 2,17$ where: y –CO_2 emission [$g \cdot m^{-2} \cdot 12h^{-1}$] x – soil temperature [$^oC$]	Szanser [1992]
	Water table	
Shallow peat bed (to 0,5m)	$y = -593,57x^2 + 4520,4x – 3916$	
Deep peat bed (>0,5m)	$y = -618,57x^2 + 5303,4x – 4544$ where: y – CO_2 emission [$kg \cdot ha^{-1} \cdot year^{-1}$] x – location of the water table [cm]	Augustin [2001]
Shallow peat bed (to 0,5m)	$y = 121x – 0,482x^2 – 121$	
Deep peat bed (>0,5m)	$y = 113x – 0,5179x^2 – 298$ where: y – CO_2 emission [$kg \cdot ha^{-1} \cdot rok^{-1}$] x – location of the water table [cm]	Renger i in. [2002]
	Soil temperature and depth of the water table	
Peat soils	$y = -15 + 2,515x_1 + 1,83x_2$ where: y – CO_2 emission [$kg \cdot ha^{-1} \cdot year^{-1}$] x_1 – soil temp. on the depth of 10cm [^oC] x_2 – location of the water table [cm]	Flessa i in. [1997]
	Soil humidity	
Peat- mucks soils	$y = 2,953 + 0,113x – 0,00093x^2$ where: y –CO_2emission [$g \cdot m^{-2} \cdot 12h^{-1}$]	Szanser [1992]

x – soil humidity [% of capacity]

Particularly interesting are equations that use the depth of the water table of the groundwater (the depth of peatlands' drainage) because this parameter is often measured in practical nature conservation, in contrary to the temperature and humidity of the soil. However, the Augustin's equation must contain an error, as it gives absurd results. A meaningful result, at least in terms of magnitude, is provided by the model created by Renger:



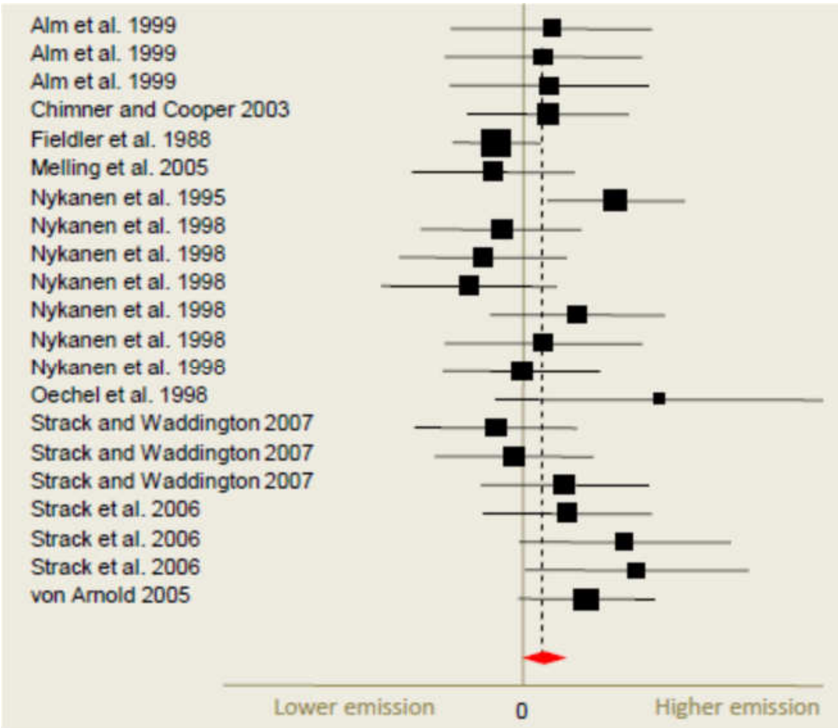
Measurements of carbon dioxide emission conducted in natural conditions with the use of different measuring methods showed that the scale of this process depends on various factors: climatic conditions, type of peatland (fen or bog), level of advancement of the mucking process, way of exploitation (arable lands or grasslands), location of water table, and the fact whether the soils are fertilized and limed. Bogs usually emit CO_2 within the range of about 9 to 20 t/ha/year. In the case of fens, it has been observed that there is much bigger diversity - from about 6 to 92 t/ha/year. However, the estimated amounts of CO_2 emission from peatlands are considerably diversified. There is not enough data to explain this diversity.

Particularly, **there is not enough data to connect the amount of emission with the ecohydrological type of peatlands.**

However, **there is a clear relationship between the CO_2 emission and the condition of peatlands in general. Peatlands in good condition accumulate CO_2. The more drained and degraded the fen is, the more CO_2 it emits.**

For example, Oleszczuk (2012) as quoted within the literature: maintaining the water table at the depth of 50 cm under the soil surface, in the case of peatlands in the Netherlands, causes the CO_2 emission on the level of 10 t/ha, and with the same depth in Florida, it reaches 40 t/ha. Lowering the water table in the above mentioned cases to the level of 90 cm causes the increase of emission up to 30 t/ha in the case of the Netherlands and 75 t/ha in the case of Florida (Wösten and Rizeba, a quote from Oleszczuk 2012). However, the further lowering of the water table and, consequently, draining of the topsoil leads to reduction in carbon dioxide emissions. Isometric research concerning the amount of CO_2 emission has been carried out in the northern part of Europe (Great Britain, Sweden) depending on the depth of water table. In the case of lowering the water table from 40 cm to 80 cm, the amount of carbon dioxide emission decreased from 919 mg m^{-2} h^{-1} to 754 mg m^{-2} h^{-1} (Bergelund and others 2007, a quote from Oleszczuk 2012). Similar research on soil monoliths collected from the peatlands in Great Britain within the particular water tables (0, 30, and 50 cm) showed much bigger discrepancy of emission, amounting to respectively: 0.6 - 1.6, 0.3 - 2.1 and 0.01 - 2.2g m^2 day^{-1}.

Within the Environmental Evidence series (the overview analyses of scientific literature concerning various environmental issues), in 2009, there was inter alia an overview concerning the greenhouse gases emission vs. peatlands re-hydratation (Bussell and others 2010). The results show that drained peatlands really emit more CO_2 than peatlands with natural hydration. The average difference was only 0.5 t of CO_2 /ha annually. However, almost all the data concern comparisons between the peatlands preserved in natural condition and those degraded. There is no research concerning the process of the peatlands' drainage. There are also only few works concerning the process of secondary irrigation (restoration of peatlands). The overview of results of different authors (a quote from Bussell and others 2010), presented in the Environmental Evidence report, showed the following:



Similar analysis within the Environmental Evidence in 2014 (Haddaway and others 2014) led to the similar results.

Temperature rise causes the increase of CO_2 emission from the drained peatlands, even disregarding the fact that the temperature rise usually means the increased level of drying. If the increased concentration of CO_2 in the atmosphere led to global warming (it is not obvious due to the complex nature of climate changes leading to the change in atmospheric circulation and ocean currents which may cause hardly predictable changes of local climates that may not always be the warming), this dependence would create the mechanism of dangerous positive feedback.

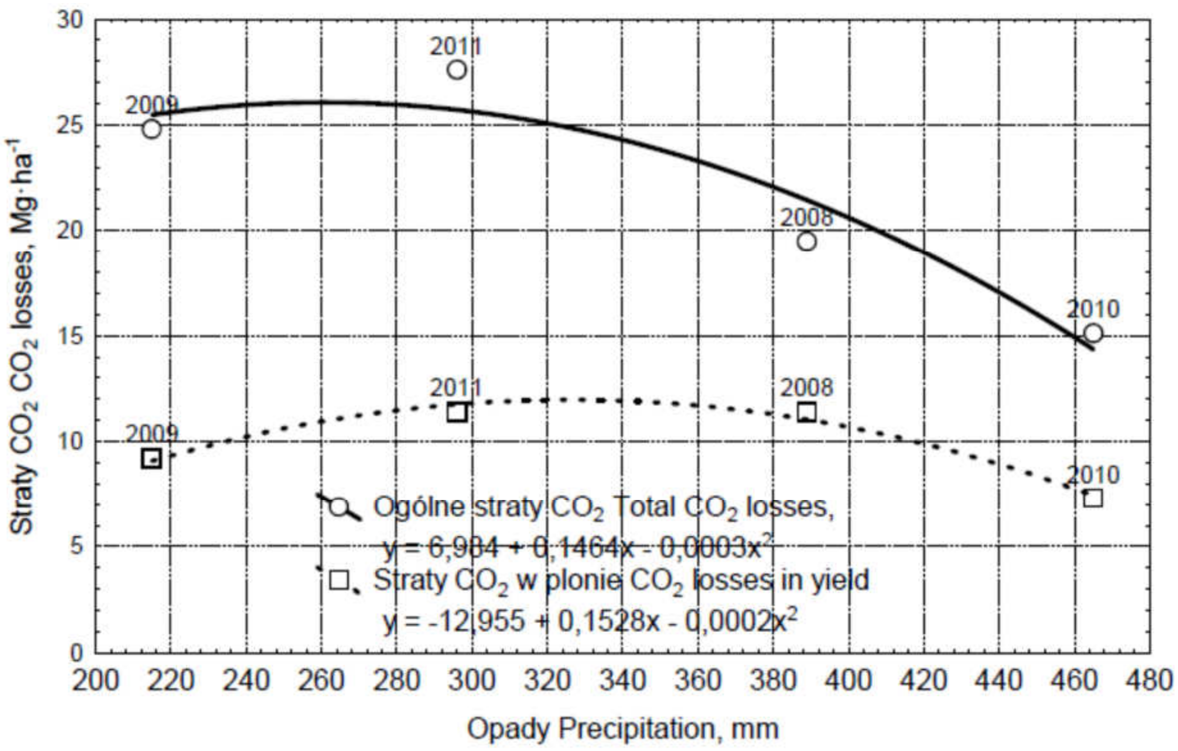
Polish estimations of the CO_2 emission and carbon balance in peatlands

There has been only a small number of Polish research on the carbon dioxide emission and on carbon balance of peatlands. The existing data concern rather the peat-muck soils, i.e. degraded and drained peatlands, analyzed as the meadow soils and, therefore, treated according to the "meadow" typology.

Turbiak and Miatkowski (2011) measured the CO_2 emission with the method of static closed chambers in the peat-muck soils of the Noteć river Valley, including post-moss soils with different level of hydtation (the average depth of water was from 18 to 118 cm, the muck layer was from 18 to 40 cm in the muck soil). The maximal emission occurred in the medium-mucked soils of moist complex (the muck layer of 30 cm) and it came to 110 t/ha annually.

Within the wet complex, the dried complex and the periodically dried complex the following emissions were observed: 66.8; 95.7; 66.5 t/ha annually. Lowering the ground water level in the summer in the wet and moist complex caused the significant increase of emission. With the full saturation of the profile with water, a retention of peatlands decomposition and the related to it CO_2 emission takes place, but during the vegetation season there is still the respiratory activity of the roots and soil microorganisms on the emission level of about 39 t/ha annually. These are very high values in comparison to the average values gathered from the data of world literature.

Turbiak (2012) studied the full carbon balance of the meadow ecosystems in the drained peat-muck soils. The meadow vegetation in the investigated areas during the vegetative season was absorbing about 78.9 t/ha CO_2, whereas the CO_2 emission of the meadow ecosystem was 90.8 t/ha CO_2. It means that the carbon loss during the vegetative season, expressed in the equivalent of CO_2, totaled at 11.9 t/ha. In the view of the carbon loss connected to the hay collection, the average CO_2 losses totaled at 21.8 t/ha. It signifies a decline of carbon in the amount of 5.9 t/ha or the loss of organic mass in the amount of 10.6 t/ha containing 56% of carbon. Analyzing the carbon balance in particular months of vegetative season it has been stated that the carbon accumulation took place only in May and was noted at the average level of -0.6 t/ha. Loss of carbon was noted during the remaining months. The greatest carbon losses, in the form of CO_2, were noticed in April -2.8 t/ha and in the months of summer, i.e. in August and July, respectively 2.40 and 2.27 t/ha. Analyzing the influence of meteorological conditions on the carbon loss in the meadow ecosystem, it has been stated that they depended mainly on the amount of precipitation. The biggest carbon losses were in the years with the small amount of precipitation, i.e. in 2009 and 2011, respectively 24.8 and 27.6 t/ha of CO_2, and the smallest losses were in the years when the amount of precipitation was higher than 380 mm, i.e. in 2008 and 2010, respectively 19.5 and 15.1 t/ha of CO_2. The author is of the opinion that the mechanism which explains this phenomenon is the stronger development of the root systems - and, consequently, their increased activity during dry years. Their development is needed due to necessity to reach water located at lower levels.



Turbiak (2014a) proved that the respiratory activity of meadow ecosystem in the peatlands soil is the smallest within the full saturation with water (1.51 g/m^2 x h), the lower the water table, the higher the activity. Turbiak (2013) estimated the carbon losses from the muck soil for about 17 t/ha annually, the biggest ones during the drying periods.

In the case of Polish fens used for the 'meadow' purposes, Czaplak and Dembek (2000) estimate the averaged amount of carbon dioxide emission into the atmosphere, basing on the pace of mineralization and indirect measurements of carbon dioxide emission. It depends on the stage of the mineralization process and the fen dampness.

Group	Area (ha)	Decline of organic matter	Decline of organic carbon	CO_2 emission into the atmosphere
		t/year		
Meadows of variable moisture content MtI	463,850	4,638,500	2,551,175	8,349,300
Fresh and dry meadows MtII	335,300	5,029,500	2,766,225	6,035,400
Fresh and dry meadows MtIII	17,650	264,750	145,612	190,620
Total	**816,800**	**9,932,750**	**5,473,012**	**14,575,320**

The above table shows that the biggest amounts of emission (about 18 t/ha/year) were observed in the case of meadows of variable moisture contents Mt I and fresh and dry meadows Mt II, the smallest amounts (about 10.8 t/ha/year) were in the case of fresh and dry meadows with high level of the mucking process.

Oleszczuk (2012), quoting Szymanowski (1999), comments on the estimates concerning the CO_2 emission from the drained fens in the Biebrza Valley, depending on their level of mucking:

Stage of mucking	CO_2 emission t/ha annually	
	Without irrigation	Irrigated
Mt I	36.5	28.5
Mt II	36.5	28.5
Mt III	21.9	17.1

Carbon carried with water

Apart from the CO_2 emission and absorption in the peatlands' areas, the carbon which is carried by water flowing out from peatlands is a crucial element of the carbon balance. This phenomenon includes:

- eluviation of the so-called particulate organic carbon (= living and non-living matter, POC = particulate organic carbon),
- eluviation of the so-called dissolved organic carbon (DOC – dissolved organic carbon),
- eluviation of the so-called dissolved inorganic carbon (carbonate and bicarbonate ions).

In this way, carbon can be transformed into carbon dioxide and emitted into the atmosphere.

Those issues have been poorly studied. Meanwhile, they can be particularly important for the alkaline fens due to the fact, that those types of fens have usually very strong water outflow and the biogeochemical processes, including carbonates and bicarbonates, are of significant importance for them. There have been no research results concerning this subject, although it may be a very important phenomenon.

The guidelines of Intergovernmental Panel on Climate Change (IPCC 2013), due to the lack of data concerning the carbon coming out from the degraded peatlands, recommend consideration of this aspect in the carbon balance only in the range of dissolved organic carbon (DOC) and only by means of very superficial rates. It is assumed that 0.08 t/ha of carbon is removed annually from natural peatlands of the boreal zone, whereas in the temperate zone the amount comes to 0.21 t/ha. The peatlands drainage increases the amount by 60%, what equals respectively 0.44 t/ha and 1.14 t/ha of carbon dioxide annually.

The upward trend of dissolved organic carbon amount in waters of the whole temperate zone has been observed over the past few decades (Freeman 2004, Evans, Monteich, Cooper 2005). It suggests the increase of the carbon emission from peatlands. There are various hypotheses concerning the explanation of this phenomena and the further prediction. Freeman (2001, 2004) claims that it is the result of increased activity of the phenolic peroxidase enzyme, caused indirectly by the increased concentration of CO_2 in the atmosphere. As a result, there is the positive feedback which additionally accelerates the climate changes and changes in the concentration of CO_2. According to the author, the carbon emission from peatlands over the last 50 years may be the same as the emission from fossil fuel burning! There are also hypotheses that the increased eluviation of DOC results from the occurring climate changes - global warming, increased surface runoff, amount of precipitation moved into the summer half-year (a quote from Freeman 2004, Evans, Monteith, Cooper 2005). However, Monteich and others (2007) suggest that the increased eluviation of DOC is the ecosystems' reaction to acidification caused by the deposition of sulphur dioxide, which means that it is possible to inhibit this process.

Although there is no data concerning the relation between the condition of peatlands, their hydration and the carbon eluviation, it can be expected that the eluviation is stronger in the case of degraded peatlands with disturbed water conditions. This aspect may be crucial for the carbon balance of peatlands, especially in case of the soligenous fens. However, there is no data for some precise estimates. Jaszczyński, Urbaniak and Nawalny (2013) stated, being at the Biebrza river, that the higher the mucking level of the muck soil, the higher the concentration of dissolved organic carbon in the water flowing from the soil. The overview analysis within the Environmental Evidence series (Haddaway and others 2014) did not reveal any correlations between the condition of peatlands (including drainage and restoration of peatlands) and the eluviation of dissolved carbon.

Other greenhouse gases

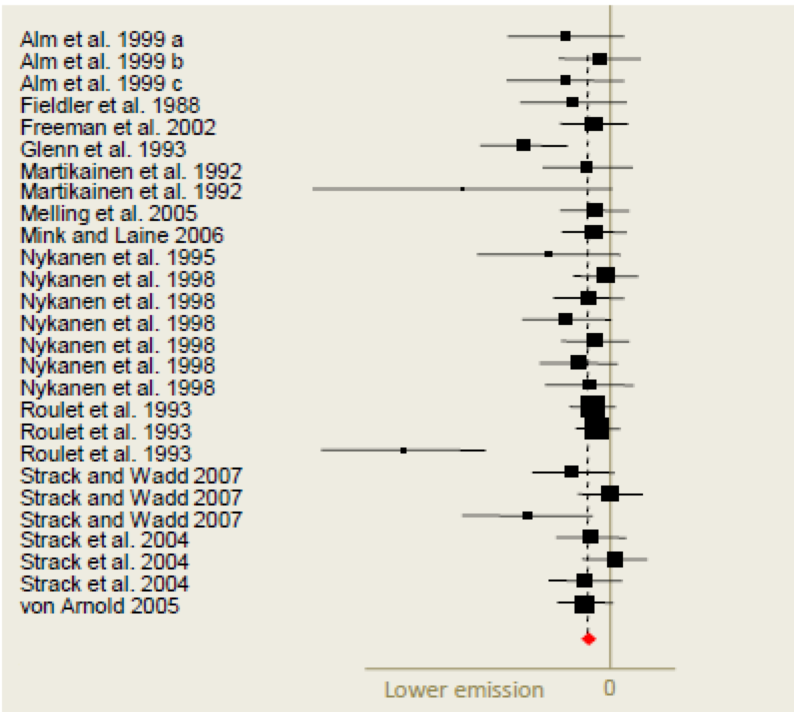
Carbon dioxide is not the only greenhouse gas. There are also methane and nitrous oxide. Their influence on the greenhouse effect refers to the influence of carbon dioxide by the equivalent rates. For example, such rate, corresponding methane for 100 years, is estimated for about 20-25, and the one corresponding to nitrous oxide, for 280-320. It means that emission of 1 million tons of methane and N_2O will give the same greenhouse effect as, respectively, 20-25 and 280-320 million tons of carbon dioxide.

Peatlands preserved in natural condition (undrained) are methane emitters which emit about 22% of the global amount of methane into the atmosphere. Their draining limits the emission of methane into the atmosphere. This process is contrary to the CO_2 emission and may - at least to some extent - eliminate the advantages of CO_2 accumulation by natural peatlands.

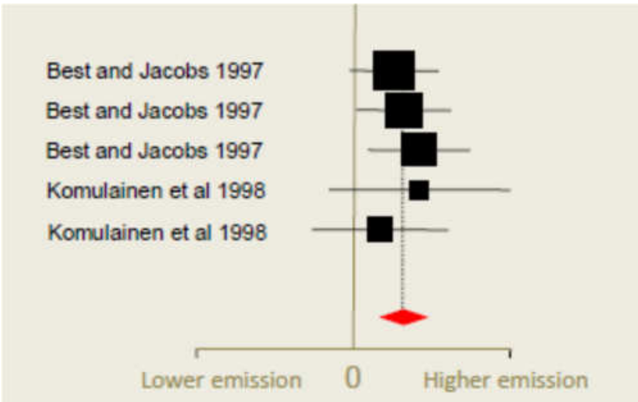
There are cases of methane emission on drained peatlands, in the spring, after thaw, by the high located water table (at the depth of about 20 cm) or after heavy precipitation. Temperature of the soil, soil pH and soil moisture are the main factors influencing the amount of CH_4 emission into the atmosphere (Oleszczuk 2012).

The guidelines of Intergovernmental Panel on Climate Change (IPCC 2013) recommend, on the basic level of approximation, consideration of the aspect in the carbon and greenhouse gases balance by the means of standard emission rates. For wet meadows in the temperate zone there is the rate of 39 kg of methane/ha annually, for forests on peatlands it is from 2 to 7 kg/ha annually, and for the completely drained peatlands used as arable lands - 0. The greatest value - 143 kg/ha annually – concerns the cultivation of rice, not present in Poland. Nevertheless, IPCC (2013) advises to add the emission from the water table stabilization trenches to the above-mentioned values. Such emission may be very high - it reaches from 217 kg/ha annually in trenches located in damp meadows and forests to about 1200 kg/ha in trenches located in badly drained peatlands.

Within the Environmental Evidence, in 2009, there was inter alia an overview concerning the greenhouse gases emission from the peatlands re-hydratation (Bussess and others 2010). The results show that the drained peatlands emit indeed less CH_4 than peatlands with natural hydration. The overview of results of different authors (a quote from Bussell and others 2010), comparing the drained peatlands with the natural ones, presented in the Environmental Evidence report, showed the following:



Analogical analysis shows that the secondary irrigation of peatlands causes the increased emission of methane:



Data presented in the quoted Environmental Evidence analysis suggest that reduction of methane emission, connected to the peatlands' draining, equilibrates or exceeds the reduction of carbon dioxide and nitrous oxide.

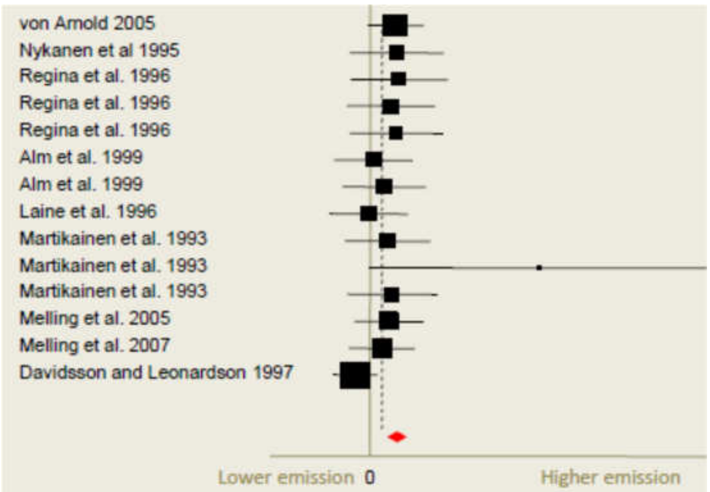
Oleszczuk (2012) quoting Stępniewska (2004, a quote from Oleszczuk 2012) states that methane emission, in conditions of muck soil of Polesie National Park, was on the lowest level - from about 0.013 t/ha/year to about 0.822 t/ha/year. The amount of emission was increasing together with the peatlands depth and was in inverse proportion to the water table. The area of intense methanogenesis on these territories is below the water table, at depth of no less than 40-50 cm. Turbiak (2012) studied the methane emission from peatlands at the Biebrza river, whereas Turbiak and Jaszczyński (2011) studied it at the Noteć river and at the Biebrza river. The greatest emission came from the fully hydrated fens. During the vegetative season, in the conditions of water table kept at the depth of 0, 25, 50, and 75 cm BGL, the average CH_4 emission totaled respectively 386, 249, 175, and 120 kg/ha, whereas in the second series of research - 502, 361, 198, 141 kg/ha. It is worth highlighting that the given values are one order of magnitude higher than the standard values recommended by IPCC (2013).

The guidelines of Intergovernmental Panel on Climate Change (IPCC 2013) recommend, on the basic level of approximation, consideration of the aspect in the carbon and greenhouse gases balance by the means of standard emission rates. The rate proposed for the wet meadows in the temperate zone is 39 kg of methane/ha annually.

Nitrous oxide (N_2O) is another greenhouse gas emitted into the atmosphere in the case of drained muck soils. Emission of this gas is on the low level, rising together with the intensity of draining. The scale of emission depends on the processes of nitrification and denitrification, amounts of NO_3, soil moisture, aeration of soil, nitrogen fertilization, soil pH and temperature. Nitrous oxide influences the greenhouse effect about 300 times stronger than carbon dioxide does.

The guidelines of Intergovernmental Panel on Climate Change (IPCC 2013) recommend, on the basic level of approximation, consideration of the aspect in the carbon and greenhouse gases balance by the means of standard emission rates. For example, the proposed rate for the forests on the drained fens in the temperate zone is 2.8 kg/ha annually, for the poorly drained meadows - 1.6 kg/ha, and for the badly drained meadows - from 4.3 to 8.2 kg/ha annually. Nyćkowiak, Leśny and Olejnik (2012) were using this method - in its previous version of 2006 - to estimate the N_2O emission from the soils of Wielkopolska Voivodship.

Within the Environmental Evidence series in 2009, there was inter alia an overview concerning the greenhouse gases emission vs. the peatlands hydratation (Bussess and others 2010). The results show that the drained fens emit indeed more N_2O than peatlands with natural hydration. However, almost all the data concern comparisons between the peatlands preserved in natural condition and the degraded peatlands. There has been no research concerning the process of peatlands draining. There are very few works concerning the process of secondary irrigation of peatlands (restoration of peatlands). The overview of results of different authors (a quote from Bussell and others 2010), presented in the Environmental Evidence report, showed the following:



According to Oleszczuk (2012), the drained muck soils of Europe emit annually from about 2 to 56 kg N_2O/ha in the European countries. Very high variability of N_2O emission was observed while conducting the field research, even on the scale of one considered quarter on the fen used as the meadow where the coefficient of variation fluctuates between 170 and 500%. The amount of nitrous oxide is smaller in the case of bogs due to the lower pH values and smaller amounts of nitrogen in comparison with peatlands.

Turbiak and others (2011) quote the results of European research on the phenomenon: in Poland, N_2O emission is expected to reach 3,9 lbs/ac annually. In Finland, the annual N_2O

emission measured by the scientists reached 16,3 lbs, yet during the growing season the emission amounted to 10,1 lbs/ac. In Holland, N_2O emission from a hay exploited peatlands at a high (0,9 ft) and low (1,6 ft) level of ground water reached 12,5 and 24,9 lbs/ac respectively. In Finland, emission from a hay peatlands was found to be lower: 4,0 lbs/ac, and in other Finnish studies – from 4,5 to 5,7 lbs/ac.

Turbiak and others (2011) found that in the Kuwasy fen in the Biebrza Valley, between August and October, N_2O emission from a peat-muck soil of meadows located in the area of the Kuwasy fens, Biebrza Valley, with the ground water level at zero ft reached 9,3 lbs/ac, and in the areas with the ground water table maintained at a depth of 0.8, 1.6 and 2.5 ft, it amounted to 10,1, 24,4 and 32,8 lbs/ac respectively. It should be noted that these are average values for the growing season, not for the full year. Nonetheless, they are higher than the European average values. In the authors' opinion, the emission value depends primarily on the water conditions in the ecosystem – it is higher in drained peatlands. They point out, however, that during long-term flooding of an area, e.g. caused by floods or fens revitalisation, N_2O emission may periodically be high due to biogeochemical processes blocking the activity of a soil enzyme – nitrous oxide reductase.

The instability and non-linearity of estimations

The above overview shows that the existing estimations on the function of peatlands in the balance of greenhouse gases and carbon, presented by different authors, vary significantly, even in the orders of magnitude. There are premises that the biogeochemical system of the fens is not a linear system, that is, emissions and removals of greenhouse gases are not a simple function of physical conditions and, potentially, a type of a peatland, but they may also depend on, for instance, peat enzymatic activity prompted and ceased in specific weather conditions (cf. Freeman, Ostle, Kang 2001, Turbiak and others 2011). The processes may also depend on petty components of a peatlands composition not included in the typical acrotelm-catotelm model (Holden 2005), whereas there may occur strong, local, and not yet identified feedbacks between weather conditions, peatlands structure, enzymatic activity and processes influencing emission and removal of greenhouse gases.

As a result, it is not clear whether the attempts to modulate the greenhouse gas balance of peatlands and to estimate 'the average emission factor' are in general methodically correct.

Valuation of ecosystem services related to carbon storage and their loss associated with the emission of greenhouse gases

If it is assumed that we can calculate the carbon balance in a natural or degraded peatlands, there comes a temptation to try to evaluate the monetary value of a carbon storing ecosystem service, or the monetary value of losses related to losing the ecosystem service due to a degradation of peatlands.

Seemingly, it is simple. There is a European market for CO_2 emission allowances. Therefore the 'price' of emitting a tonne of CO_2 is known, and so are the conversation rates allowing other gas emission to be converted into an equivalent amount of carbon dioxide. As at July 2014 (NCEBM 2014 [National Centre of Emission Balancing and Management]), the average price of an allowance to emit one tonne of CO_2 (so called EUA) was approximately € 6. By rough and ambitious estimations, maintaining an ordinary alkaline fen in a natural, undrained, state, which entails avoiding emission of approximately 4 t of CO_2/ac annually, would generate a profit of approximately € 60 annually. This is a rather upper limit of such estimation. If the difference in the CO_2 emission between a natural and drained fens were rather of 0,2 t/ac annually, the profit would be estimated to reach a negligible sum of €1.2/ac.

In reality, however, the price of EUA does not properly represent the value of ecosystem services relevant to preventing the increase in emission of carbon dioxide and other greenhouse gases. The actual value of these services, per tonne of the emitted CO_2, should rather be calculated as an equivalent of the value of losses caused by climate change. Though for such a calculation there is no data – and probably never will be - that is realistic enough.

Estimation of the impact of the LIFE11 NAT/PL/423 project "Protection of alkaline fens (7230) in the young-glacial landscape of northern Poland"

As part of the project, protective measures have been implemented that have changed the water and vegetation conditions on peatland covered by project activities. It can therefore be assumed that they also changed the ability of particular peatlands to absorb and emit greenhouse gases, modifying the balance of these gases on them. However, no specific research was carried out that could illustrate this effect.

The only method that in this situation may give any estimation of the impact of the project on the greenhouse gas balance, seems to be the method assuming that the specified vegetation of the peatland under specific water conditions are characterized by constant emission and absorption factors of greenhouse gases (and consequently a constant factor of Global Warming Potential (GWP - expressed in tons of CO_2 equivalent/ha/year), and change in vegetation results in a change in the emission and absorption factors to values corresponding to the new vegetation type, i.e. vegetation is assumed to be a good greenhouse gas balance estimate for the covered by this vegetation fragment of the peatland.

This approach was proposed by Couwenberg et al. (2008, 2011) as the so-called GEST method. It consists in distinguishing and scaling the so-called “Emission Habitats Types” on the peatland - Greenhouse-Gas-Emissions-Site-Types (GEST), and then assigning to each of these habitat types values of emission factors or greenhouse gas absorbers, determined as averages from the results of many tests (measurements) performed on different peatlands and in different time, but in a given type of habitat. Under this approach, there is a catalog of Emission Habitat Types, providing for each type of habitat CO_2, CH_4 and total Global Warming Potential (GPW) balance, expressed in tons of CO_2/ha equivalent per year.

Both basic assumptions of this method (the possibility of approximation of emission and absorption coefficients based on the Emission Habitat Type determined by vegetation reacting to water conditions and immediately changing these coefficients corresponding to the change of vegetation) are very simplifying. According to Pawlaczyk and Kujawa-Pawlaczyk (2017), such methods may prove useful in the estimates for a larger group of peatlands, eg in analyzes for policy purposes on a national or large scale, although for a specific peatland they are and will remain very uncertain. However, at least a very rough estimate can be obtained in this way.

To estimate the impact of the implementation of the project LIFE11 NAT/PL/423 “Protection of alkaline fens (7230) in the young glacial landscape of northern Poland” on the greenhouse gas balance on all sites (in total 619.1 ha), based on data collected as part of vegetation and water conditions monitoring, the structure of the Emission Habitat Types was determined before the implementation of protective measures and after their implementation. Emission factors or GHG emission absorbers were adopted for individual Emission Type Habitats based on the latest available analysis - a working GEST catalog prepared under another LIFE project - "Reduction of CO2 emissions by renaturalization of degraded peat bogs in northern European lowlands", LIFE PeatRestore LIFE15 CCM / DE / 000138" (Hermann 2018).

The Emission Habitat Types adapted to the diversity of vegetation and aquatic conditions of alkaline fens in northern Poland were distinguished, attributing them to the distinguished Hermann catalog (2018) of pan-European Emission Habitat Types and taking for them from this catalog relevant emission or absorption coefficients of CO_2, CH_4 and total Global Warming Potential. The following types and coefficients were adopted:

Category	CO_2 emission tones/ha per year	CH_4 emission equivalent CO_2 tones/ha per year	GWP equivalent CO_2 tones/ha per year
CATEGORY: Wet tall sedges reeds	-0,1	8,5	8,4
CATEGORY: [Meso-Eutrophic] Moist forest ans shrubberies	4,6	7,5	12,2
CATEGORY: Wet small sedges reeds mostly with moss layer	-3,5	6,8	3,3

CATEGORY: Very moist Meadows, forbs and small sedges reeds	-0,5	2,1	1,6
CATEGORY: (Meso-eutrophic] Modearely moist Forests and shrubberies	4,6	7,5	12,2
CATEGORY Wet peat moss lawn	-0,5	0,3	-0,3
CATEGORY: Flooded Phragmites & Phalaris reeds	-15,7	13	-2,7
CATEGORY: Flooded Tall Sedges reeds & Typha-Reeds	1,2	14,6	15,8
CATEGORY: open water/ditches	0	2,8	2,8
CATEGORY: [Meso-eutrophic] Very moist Forests and shrubberies	-0,5	1,1	1,6
CATEGORY: Wet tall reeds	-2,3	6,3	4
CATEGORY: extremely flooded Reeds (>20 cm above surface)	-32,8	33,6	0,8
CATEGORY: [Meso-eutrophic] Wet Forests and shrubberies	0	5,8	5,8
CATEGORY: Moderately moist (forb) meadows	24	0	24
CATEGORY: Moist reeds and (forb) meadows	4,6	7,5	12,2
CATEGORY: Wet peat moss hollows resp. flooded peat moss lawn	-3,1	12	8,9
CATEGORY: Wet Meadows and forbs	0	5,8	5,8

The results of calculations lead to the estimation that the activities implemented as part of the project have reduced Global Warming Potential by an equivalent of 317.6 tons of CO_2 per year, ie by 0.51 tons of CO_2/ha per year.

The change of the GWP was identifiable among 16 out of 40 analyzed facilities, with the GWP lowering on 14 sites (the largest on Gogolewko site by 79 tons of CO_2 per year, Manowo by 61 tons of CO_2 per year, Mielęcin Bukowo by 31 tons of CO_2 per year, Zapceń by 262 tons of CO_2 per year). At two sites, the estimated GEST Global Warming Potential method has increased - Nowa Studnica by 13 tons of CO_2 per year, Stara Korytnica by 7 tons of CO_2 per year, which, however, may be an artefact resulting from very simplifying assumptions of the method.

Conclusions drawn worldwide and in Europe

Despite significant differences in estimations, an agreement that modification – in particular, desiccation and degradation of peatlands - has a negative influence on the carbon balance, causing the increase in greenhouse gas emission, is quite common. Although degradation of peatlands reduces the processes of metagenesis and methane emission which takes place within them, at least according to some study results – in case of peatlands degradation and peat deposit decay – the increase in CO_2 and N_2O emission as well as the increase in carbon removal by water overweigh the reduction of methane emission. Therefore protection and preservation of natural peatlands is suggested as an important element in curbing climate change. Bussell and others (2010) comparison provides contrary conclusions though.

Restoration, re-naturalisation, of peatlands – frequently consisting in re-irrigation – is also pointed out as an element of curbing climate change. In this case, however, climatic effect is not clear. The existing evidence that properly irrigated peatlands are more advantageous, from a point of view of the greenhouse gas balance, than drained peatlands concerns in vast majority comparison of peatlands degraded in varying degrees. It does not indicate at all that it is enough to irrigate a degraded peatlands in order to improve the greenhouse gas balance. There are only a few real analyses of effects of re-irrigation on the greenhouse gas balance (Strack 2008, Bussel and others 2010, Beyer and Höper 2014 and the sources quoted), and their results are not clear. Re-naturalising peatlands may have positive effects on the greenhouse gas balance rather in a long-time perspective by restoring the peat forming process (Schumann and Joosten 2008). A correct re-naturalisation of peatlands probably has the potential to improve the greenhouse gas balance, but this issue is not at all clear (Worall and others 2010).

Suggestions concerning curbing climate change by protection, restoration (rehabilitation) and sustainable use of peatlands were gathered by Joosten, Tapio-Biso and Tol (2012) in a textbook published by Wetlands International organisation. Their primary message is that wet peatlands should be sustained wet, and desiccated peatlands should be re-irrigated. The authors provide examples of economic and social benefits achieved in fens sustained in a boggy state or brought back to their boggy state.

Basing on the conviction that peatlands play a role in the world's carbon sequestration, models of agricultural use of peatlands maintaining their irrigation – so called paludicultures, postulating acquiring and using this portion of biomass which is not necessary for the peat forming process – to be developed. Examples of these can be the attempts of sphagnum farming for the horticultural industry, acquisition and the use of peat biomass for the production of insulation materials, or, as well, alder forestry. These models represent an attractive compromise between peatlands protection and its agricultural use; the actual influence of the models on the processes of greenhouse gas accumulation and removal is not well understood though. Furthermore, such use of peatlands may transform them strongly and impact peatlands' biodiversity negatively: even if afforesting soligenic peatlands with alder contributed to higher carbon accumulation in these areas, it is a method of land-use that should not be recommended.

In the literature, one may find proposals of 'peatlands geoengineering', which are to optimise the influence of peatlands on the climate, and which consist of introducing genetically modified sphagnum, fertilising peatlands with ammonium sulphate, or embedding wooden pales in a peatland which would ultimately remain in it as accumulated carbon resources (Freeman, Fenner and Shirsat 2012).

Conclusions drawn from this analysis

1. There are convincing arguments that **from the point of view of curbing climate change by limiting greenhouse gas emission it is vital to protect and preserve natural peatlands in good condition.** Quantitatively, the role of peatlands in the greenhouse gas balance is significant almost for sure. However, credible quantitative estimations of this role seem to be impossible due to complexity of mechanisms of carbon biogeochemistry of peatlands, separateness of various peatlands structures and imperfections in the existing measuring methods.
2. Perhaps restoration of peatlands water conditions of peatlands is in total beneficial from the point of view of limiting greenhouse gas emission. However, in real peatlands areas, as a result of peatlands restoration, different effects may occur, including the increase in greenhouse gas emission.
3. There is no data that would allow for formulating specific conclusions on this subject for alkaline soligenic fens, that is, for a Natura 2000 habitat 7230, i.e. in the current state of knowledge, there are no premises to favor these fens over other types of peatlands in respect to the role in the greenhouse gas balance.
4. The proposed 'compromise' – even in protected areas – between protecting peatlands and enabling their agricultural exploitation as grassland (such exploitation is, in many cases, the condition for preserving biodiversity), in which – taking into account operating potential of typical farming machineries – it is suggested to maintain the water level at approximately 0.9 ft beneath the ground level, with periodical lowering to 2.6 ft beneath the ground level during hay-cutting period, which is exactly the water regime that maximises greenhouse gas emission from peatlands. If one wants to protect peat deposits and use peatlands for carbon accumulation, while simultaneously mow their vegetation in order to preserve biodiversity, then such a scheme would have to be implemented as specific 'peatlands agriculture': with an

adjustment of farming practices and machineries to water conditions, not the other way round.

5. Attempts to financially evaluate the value of an environmental service consisting in carbon accumulation in a particular peatland do not have, and probably never will have, reasonable grounds. In the current state of knowledge, we already know that mechanisms of carbon biochemistry of the peatlands are complex and non-linear; in particular, they may function by way of ‘switching’ between different processes after crossing threshold conditions, or there may as well occur positive and negative feedbacks within them. It means that estimating peatlands carbon balance on the basis of standard average values for specific types of peatlands and for the set abiotic conditions, even though it may be useful for estimating global emissions, is not and will not be appropriate for an individual and particular fens. Even if we knew these mechanisms fully, then, obtaining input data for a credible estimation of greenhouse gas emission for a particular peatlands would, and will remain, more expensive than the result of the evaluation, i.e. the monetary value of greenhouse gas emission or absorption, no matter how it is calculated.
6. Attempts to follow such evaluation endeavours when making a decision on the method of protecting peatlands would be additionally very risky. Although, at a very general level, preserving natural peatlands coincides with maintaining theirs role as areas of carbon accumulation, but more thorough ‘geoengineering’ attempts to maximise peatlands’ uptake of greenhouse gases may be destructive for peatlands ecosystems and their biodiversity.

Bibliography

Artz, R., Chapman., S., Donnelly, D. and Mathews R. 2012. Potential Abatement from Peatland Restoration. Research Summary. Climate Exchange.

Aurela, M., Riutta, T., Laurila, T., Tuovinen, J-P., Vesala, T., Tuittila, E-S., Rinne, J., Haapanala, S., Laine, J. 2007. CO2 exchange of a sedge fen in southern Finland - the impact of a drought period. Tellus B 59: 826-837.

Berglund Ö., Berglund K., Persson L. 2007. Effect of drainage depth on the emission of CO2 from cultivated organic soils. W: Wetlands: Monitoring, Modelling and Management. T. Okruszko, E. Maltby, J. Szatyłowicz, D. Świątek, W. Kotowski (Eds). Taylor & Francis Group, London: 133-137.

Beyer C, Höper H. 2014. Greenhouse gas emissions from rewetted bog peat extraction sites and a *Sphagnum* cultivation site in Northwest Germany. Biogeosciences Discuss., 11, 4493–4530.

Blodau C., Siems M., Beer J. 2011. Experimental Burial Inhibits Methanogenesis and Anaerobic Decomposition in Water-Saturated Peats. Environ. Sci. Technol., 2011, 45(23): 9984–9989.

Brandyk T., Szatyłowicz J., Oleszuk R., Gnatowski T. 2003. Water-related physical attributes of organic soils. In: Organic soils and peat materials for sustainable agriculture. L.E. Parent, P. Ilnicki (Eds), CRC Press, Boca Raton: 33-66.

Bussell, J. , Jones, D.L., Healey, J.R. & Pullin, A.S. 2010. How do draining and re-wetting affect Carbon stores and greenhouse gas fluxes in peatland soils? Environmental Evidence CEE 08-012.

Byrne K.A., Chojnicki B., Christensen T.R., Drösler M., Freibauer A., Friborg T., Frolking S., Lindroth A., Mailhammer J., Malmer N., Selin P., Turunen J., Valentini R., Zetterberg L. 2004. EU Peatlands: Current Carbon Stocks and Trade Gas Fluxes, report 7/2004, specific study 4, s. 58.

Charman D. J., Beilman D.W., Blaauw M., Booth R. K., Brewer S., Chambers S. F. M., Christen J. A., Gallego-Sala A., Harrison S. P., Hughes P. D. M., Jackson S. T., Korhola A., Mauquoy D., Mitchell F. J. G., Prentice I. C., van der Linden M., De Vleeschouwer F., Yu Z. C., Alm J., Bauer I. E., Corish Y. M. C. , Garneau M., Hohl1 V., Huang Y., Karofeld E., Le Roux G., Loise J., Moschen R., Nichols J. E., Nieminen T. M., MacDonald G. M., Phadtare N. R., Rausch N., Sillasoo U., Swindles G. T., Tuittila E-S. Ukonmaanaho L., Valiranta M., van Bellen S., van Geel B., Vitt D. H., Zhao Y. 2013. Climate-related changes in peatland carbon accumulation during the last millennium. Biogeosciences, 10, 929–944.

Couwenberg J. 2009. Emission factors for managed peat soils (organic soils, histosols) An analysis of IPCC default values. Wetlands International.

Couwenberg, J., J. Augustin, D. Michaelis & H. Joosten, 2008. Emission Reductions from Rewetting of Peatlands. Towards a Field Guide for the Assessment of Greenhouse Gas Emissions from Central European Peatlands. Duene/RSPB, Greifswald/Sandy.

Couwenberg J., Thiele A., Tanneberger F., Augustin J., Bärisch S., Dubovik D., Liashchynskaya N., Michaelis D., Minke M., Skuratovich A., Joosten H. 2011. Assessing greenhouse gas emissions from peatlands using vegetation as a proxy. Hydrobiologia 674: 67-89.

Czaplak I., Dembek W. 2000. Torfowiska Polski jako źródła emisji dwutlenku węgla. Zeszyty Edukacyjne IMUZ 6: 61-71.

Evans C. D., Monteith D.T., Cooper D.M. 2005. Long-term increases in surface water dissolved organic carbon: Observations, possible causes and environmental impacts. Environmental Pollution 137, 1: 55–71

Fenner N., Freeman C. 2011. Drought-induced carbon loss in peatlands. Nature Geoscience 4: 895–900

Freeman C., Fenner N., Shirsat A. H. 2012. Peatland geoengineering: an alternative approach to terrestrial carbon sequestration. Phil. Trans. R. Soc. A 2012 370.

Freeman C., Fenner N., Ostle N. J., Kang1 H., Dowrick D. J., Reynolds B., Lock A. A., Sleep D., Hughes S, Hudson J. 2004. Export of dissolved organic carbon from peatlands under elevated carbon dioxide levels. Nature 430, 195-198.

Freeman C., Ostle N., Kang H. 2001. An enzymic 'latch' on a global carbon store. Nature 409: 149.

Freeman C.. Evans D., Monteith D. T., Reynolds B., Fenner N. 2001. Export of organic carbon from peat soils. Nature 412: 785

Haddaway N. R., Burden A., Evans C. D., Healey J. R., Jones D. L., Dalrymple S. E., Pullin A. S. 2014. Evaluating effects of land management on greenhouse gas fluxes and carbon alances in boreo-temperate lowland peatland systems. Environmental Evidence 2014, 3:5.

Hermann A. 2018. Updated GEST Catalogue 2.0. Mscr. LIFE Peat Restore LIFE15 CCM/DE/000138 „Reduction of CO2 emissions by restoring degraded peatlands in Northern European Lowland“.

Holden J. 2005. Peatland hydrology and carbon release: why small-scale processes matters. Phil. Trans. R. Soc. A 2005 363.

Holmgreen et al. 2011. PeatImpact. Greenhouse gas calculation methodologies for fuels based on peat and peat grown biomass. Service contract to improve understanding of greenhouse gas impacts of using peat or peat grown biomass for transport fuels or other types of energy. Contract no 070307/2009/546431/SER/C3 - Final report.

Ilnicki P. Iwaszyniec P. 2002. Emissions of greenhouse gases (GHG) from peatland. In: Restoration of carbon sequestration capacity and biodiversity in abandoned grassland on peatland in Poland. P. Ilnicki (Red.), Wydawnictwo AR Poznań, s. 19-57.

IPCC (2006) 2006 IPCC guidelines for national greenhouse gas inventories, prepared by the National Greenhouse Gas Inventories Programme (eds. Eggleston HS, Buendia L, Miwa K, Ngara T, Tanabe K). IGES, Japan.

IPCC 2014, 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands, Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M. and Troxler, T.G. (eds). Published: IPCC, Switzerland

Janssens, I. A., Freibauer, A., Schlamadinger, B., Ceulemans, R., Ciais, P., Dolman, A. J., Heimann, M., Nabuurs, G.-J., Smith, P., Valentini, R., Schulze, E.-D. 2005. The carbon budget of terrestrial ecosystems at country-scale – a European case study. Biogeosciences 2: 15-26.

Jaszczyński J., Urbaniak M., Nawalny P. 2013. Wpływ stopnia zmurszenia gleb torfowych na wzbogacanie wody gruntowej w związki azotu, fosforu i RWO. Woda--Środowisko-Obszary Wiejskie. 13, 3(43): 63–77.

Joosten 2010. The Global Peatland CO_2 Picture. Peatland status and drainage related emissions in all countries of the world. Wetlands International.

Joosten H., Tapio-Bistrom M. L., Tol S. 2012. Peatlands - guidance for climate change mitigation through conservation, rehabilitation and sustainable use. Food and Agriculture Organization of the United Nations and Wetlands International.

Jurczuk S. 2012. Emisja dwutlenku węgla ze zmeliorowanych gleb organicznych w Polsce. Woda-Środowisko-Obszary Wiejskie 12, 3(39): 63-76.

Klimkowska A. 2008. Restoration of severely degraded fens: ecological feasibility, opportunities and constraints. PhD thesis, University of Antwerp.

KOBiZE 2014. Raport z rynku CO_2. Lipiec 2014 r. Krajowy Ośrodek Bilansowania i Zarządzania Emisjami, 9 str.

Lindroth, A., Lund, M., Nilsson, M., Aurela, M., Christensen, T.R., Laurila, T., Rinne, J., Riutta, T., Sagerfors, J., Ström, L., Tuovinen, J.-P. 2007. Environmental controls on the CO2 exchange in north European mires. Tellus B 59: 812–825.

Madsen K., Ebmeier S. 2012. Petlands and climate change. Scottish Parliament Information Centre Biefing.

Monteith D. T., Stoddard J. L., Evans C. D., de Wit H. A., Forsius M., Høgåsen T., Wilander A., Skjelkvåle B. L., Jeffries D. S., Vuorenmaa J., Keller B., Kopácek J., Vesely J. 2007. Dissolved organic carbon trends resulting from changes in atmospheric deposition chemistry. Nature 450, 537-540.

Nyćkowiak J., Leśny J., Olejnik J. 2012. Ocena bezpośredniej emisji N_2O z gleb użytkowanych rolniczo województwa wielkopolskiego w latach 1960–2009 według metodologii IPCC. Woda-Środowisko-Obszary Wiejskie. T. 12. Z. 4(40) s. 203–215.

Nykänen H., Alm J., Lang K., Silvola J., Martikainen P.J. 1995. Emissions of CH_4, N_2O and CO_2 from a virgin fen and a fen drained for grassland in Finland. J. Biogeography 22: 351-357.

Okruszko H. 1993. Transformation of fen-peat soils under the impact of draining. Zeszyty Problemowe Postępów Nauk Rolniczych 406: 3-73.

Oleszczuk R. 2006. Analysis of shrinkage process of raised bog peat. Polish J. Environ. Stud. 15(5d): 86-89.

Oleszczuk R. 2012. Wielkość emisji gazów cieplarnianych i sposoby jej ograniczania z torfowisk użytkowanych rolniczo.. W: Wybrane problemy ochrony mokradeł. Wspólczesne problemy kształtowania i ochrony środowiska, Monigrafie 3.

Oleszczuk R., Regina K., Szajdak L., Höper H., Maryganova V. 2008. Impact of agricultural utilization of peat soils on the greenhouse gas balance. W: Peatlands and Climate Change. M. Strack (Ed.), International Peat Society, Jyväskylä, Finlandia: 70-97.

Olszta W., Jaros H. 1991. Wpływ intensywnego odwodnienia na zdolności zatrzymywania wody, kurczliwości oraz przewodnictwa kapilarnego gleb torfowomurszowych. Wiad. IMUZ 16(3): 37-56.

Păcurar I.; Clapa D., Şandor M, Sână S., Şotropa A., Dunca M., Buta M. 2010. Research on CO2 Emissions from Peat Bog "Valea Morii", Cluj County. ProEnvironment Promediu 3, 6: 375.

Pawlaczyk P., Kujawa-Pawlaczyk J. 2017. Wybrane problemy monitoringu i oceny stanu torfowisk oraz ich usług ekosystemowych. Studia i Materiały CEPL w Rogowie 19(51), 2: 103-121.

Schumann M., Joosten H. 2008. Global Peatland Restoratioon Manual. Institute of Botany and Landscape Ecology, Greifswald University, Germany.

Strack M. (ed.) 2008. Peatlands and Climate Change. International Peat Society.

Turbiak J. 2012. Bilans węgla w ekosystemie łąkowym na średnio zmurszałej glebie torfowo-murszowej. Woda – Środowisko - Obszary Wiejskie 12,4(40): 281-294.

Turbiak J. 2012. Methane emission from peat-muck soil in the Biebrza river valley in relation to ground water level and fertilisation. J. Water Land Dev. 17: 77-82.

Turbiak 2013. Ocena ubytku masy organicznej w glebie murszowatej na podstawie pomiarów strumieni emisji dwutlenku węgla. Woda – Środowisko - Obszary Wiejskie 13,2(42): 147-159.

Turbiak J. 2014. Ocena wpływu poziomu wody gruntowej na wartość wymiany CO_2 między ekosystemem łąkowym a atmosferą w warunkach doświadczenia lizymetrycznego. Woda – Środowisko - Obszary Wiejskie 14,2(46): 115-125

Turbiak J. 2014. Wpływ intensywności użytkowania łąki na glebie torfowo-murszowej na wielkość strumieni CO_2 i jego bilans w warunkach doświadczenia lizymetrycznego. Woda-Środowisko-Obszary Wiejskie. T. 14. Z. 2(46) s. 127–140.

Turbiak J., Jaszczyński 2011. Emisja metanu z gleb torfowo-murszowych w zależności od poziomu wody gruntowej. Woda – Środowisko - Obszary Wiejskie 11, 4(36): 229-238.

Turbiak J., Miatkowski Z., Chrzanowski S., Gąsiewska A., Burczyk P. 2011. Emisja podtlenku azotu z gleby torfowo-murszowej w dolinie Biebrzy w zależności od warunków wodnych. Woda – Środowisko - Obszary Wiejskie 11, 4(36): 239-245.

Turbiak J., Miatkowski Z. 2010. Emisja CO2 z gleb pobagiennych w zależności od warunków wodnych siedlisk. Woda – Środowisko - Obszary Wiejskie 10, 1(29: 201-210.

Turbiak J., Miatkowski Z. 2011. Wpływ warunków wodnych i intensywności użytkowania na bilans węgla w glebach pobagiennych. Nauka, Przyroda, Technologie 5, 5: 1-9.

Worrall F., Chapman P., Holden J., Evans C., Artz R., Smith P., Grayson R. 2010. Climate Change Mitigation & Adaptation Potential. Draft scientific review. IUCN UK Peatland Programme's Commission of Inquiry into Peatland Restoration.