CHAPTER 7:

RESTORATION OF PEATLANDS AND GREENHOUSE GAS BALANCES

H. Höper[1], J. Augustin[2], J.P. Cagampan[3], M. Drösler[4], L. Lundin[5], E. Moors[6], H. Vasander[7], J.M. Waddington[3], D. Wilson[8]

1. State Authority for Mining, Energy and Geology, Monitoring of Soil and Groundwater, Germany
2. Leibniz Centre for Agricultural Landscape Research (ZALF), Institute of Landscape Matter Dynamics, Germany
3. School of Geography and Earth Sciences, McMaster University, Canada
4. Vegetation Ecology, Technische Universität München, Germany
5. Department of Forest Soils, Swedish University of Agricultural Sciences, Sweden
6. Alterra, Centre for Water and Climate, The Netherlands
7. Department of Forest Ecology, University of Helsinki, Finland
8. School of Biology and Environmental Science, Agriculture and Food Science Centre, University College Dublin, Ireland

7.1. Introduction

As recently as the 1970s and 1980s in Europe and North America the use and drainage of peatlands was the primary objective of peatland management. However, over the last two decades the restoration of peatlands has gained importance. The role of peatlands in global biodiversity and their importance for endangered species of fauna and flora has been more and more realized. Wetlands, including peatlands, have been rewetted as habitats, especially for migratory and breeding birds following the European Natura 2000 convention.

An accurate estimate of the area of restored peatlands in Europe and Northern America is not available. Nevertheless, some facts may underline the growing importance of peatland restoration in the upcoming decennia. In Lower Saxony, one of the Northern states of Germany where two thirds of German bogs are situated, a bog protection programme was started in 1985. To date, about 20 % of the 2500 km² initial bog area has been included into nature protection areas. Special emphasis was placed on the after-use of peat excavated areas. Currently, 42 % of former cutaway areas are nature conservation areas. With the expiration of extraction rights, a further 23 500 ha (corresponding to 82 % of the current peat extraction area) will be allowed to regenerate (NLWKN, 2006). In Sweden, about 500 to 1000 ha, i.e. 5 % of the cutover area, are presently restored and a prognosis of 5000 ha or 30 % of the peat cut area is given for 2010 (Vasander *et al.*, 2003). For Ireland it is estimated that around 30 000 ha could be available for rewetting or restoration over the next 20-30 years. These will also come out of industrial peat production. In Canada 1 800 ha of excavated peatland are currently in process of restoration or reclamation and 3 100 ha are projected for restoration or reclamation until 2011 (Canadian Sphagnum Peat Moss Association, CSPMA, unpublished). The restoration of fens is still less widespread, as fens are frequently very fertile agricultural land. Nevertheless, about 10 000 ha of grassland fens have been rewetted in Northeast Germany (LUNG, 2006) and 2 500 ha in North West Germany (NLWKN, 2007). Similarly, in the Netherlands and Colorado efforts have been made to restore fens (Cooper & MacDonald 1998; 2000).

Restoration of a disturbed peatland is the attempt to establish, as far as possible, the conditions for peat growth. However, disturbance may often lead to irreversible changes in peat structure, peat composition, peat (land) hydrology and peatland position in the landscape (Schouwenaars, 1993). This makes it difficult to re-establish the conditions that are essential for the formation and growth of the peatland. Additionally, factors such as climate change and eutrophication could impede or reduce peat formation at the local or global level. Thus, in contrast to past conditions, it is not always certain that the conditions favourable for peat growth will lead to sustainable peat formation in the forthcoming centuries or even millennia. Moreover for the assessment of the net climate effect of peatland restoration, peat growth alone is not sufficient as an indicator, as the exchange of climatically relevant trace gases rules the climate effect.

A systematic overview on the exchange of greenhouse gases in restored peatlands is not available as direct measurements of gas emissions are scarce. Additionally, the starting conditions are very heterogeneous from one site to the other, as has been shown for former peat cutting areas (Blankenburg & Tonnis, 2004). Thus, in this chapter, several examples will be given, covering the most important regions (temperate and boreal) and peat types (fens and bogs) of non-tropical peatlands.

In this chapter the impact of peatland restoration on greenhouse gas fluxes will be discussed based on a literature review. As the starting conditions for restoration experiments and restoration techniques are very diverse, not all combinations of the involved factors can be taken into account. Moreover, direct measurements of greenhouse gas emissions are very laborious and expensive, and, therefore, only few examples on greenhouse gas emission measurements from restored peatlands exist. In the following, case-studies will be presented covering different peatland types, different regions and different starting conditions.

7.2. Restoration techniques and factors involved in greenhouse gas emissions

The success of peatland restoration and its impact on greenhouse gases fluxes is strongly dependent on the time elapsed since the end of peatland use or excavation, the starting conditions, and on the restoration techniques. Gorham & Rochefort (2003) suggest that peatland restoration should occur immediately after extraction to reduce degradation at the peat surface, preventing irreversible hydrological changes and potentially returning the carbon sink functions of the ecosystems. In regard to the starting conditions, two general types are distinguished here (1) the restoration of peat cutting areas (section 7.3) and (2) the restoration of peatlands formerly used for agriculture or forestry (section 7.4).

Concerning restoration following peat extraction, Blankenburg & Tonnis (2004) defined a number of starting conditions based on residual peat depth and peat type, landscape situation and cutting method. Concerning the cutting method, a different restoration success was observed for block-cut and milled peat production or vacuum extracted peatlands: Block-cut cutover peatlands can regenerate to an extent due to *Sphagnum* diaspores that remain combined with residual micro topography of the baulks and trenches which aid in sustaining adequate soil moisture and soil-water tension for *Sphagnum* reestablishment. However, only 17.5% of abandoned blocked-cut bog trenches in Quebec had *Sphagnum* covers greater than 50% (Poulin *et al*., 2005). The potential for natural regeneration of vacuum extracted cutover peatlands is much lower because of greater degradation of hydrological conditions from mechanized extraction and complete removal of plant material. Ferland & Rochefort (1997) observed that the vacuumed peat surfaces dry out quickly even if the water table is close to the surface hindering the ability of *Sphagnum* to re-establish on the peat surface.

Self-regeneration of peatlands can occur but often leads to limited recovery of pre-extraction functions. Recent North American studies even suggest that non-restored cutover peatlands represent a persistent source of atmospheric CO_2 (e.g. Waddington & Price, 2000). Therefore, human activities are frequently involved in order to accelerate the regeneration process. The most commonly used restoration techniques include reduction of land-use intensity or ending of land-use, artificial topography, rewetting by blocking drainage ditches or by flooding from passive or pumped seepage reservoirs, introduction of peat forming plants (e.g. *Sphagnum* species) or companion species, and straw mulch application. Concerning water supply, Schouwenaars (1988) suggested that effective *Sphagnum* re-establishment in cutover peatlands should occur where the water table does not drop more than 40 cm below surface. *Sphagnum* growth in a cutover peatland is limited not only by water availability but also by drying and wetting cycles (McNeil & Waddington, 2003). These moisture cycles can suppress photosynthesis for a prolonged period of time and enhance respiration losses. The evaporative water loss over summer can especially impact carbon dynamics within a peatland (Waddington & Price, 2000). Moreover, the degree of degradation of the peat hydraulic properties (i.e. hydraulic conductivity and soil-water tension relationships) under past drainage and land-use measures determines the swelling and the porosity of the peat after rewetting, and, thus, the moisture conditions for *Sphagnum* colonization. Companion species might be important as it has been observed that the growth of *Sphagnum* is strongly dependent on the presence of vascular plants (i.e. ericaceous shrubs; McNeil & Waddington, 2003), or with *Polytrichum strictum* at the early stages of restoration (Groeneveld *et al*., 2007).

Of course, the starting conditions (i.e. degree of peat degradation, water supply, evaporative water loss, presence of companion species) and the above mentioned restoration techniques have an impact on the emission of greenhouse gases. Firstly, they affect the productivity of the peat forming plants and, thus, the process of peat accumulation which represents a continuing sink for carbon dioxide (CO_2). Secondly, rewetting inhibits methane (CH_4) oxidation at the peat surface and CH_4, which is formed in the anoxic zones, is emitted directly to the atmosphere. This depends strongly on the water table, as a mean water table below 10 cm seems to be sufficient in preventing accelerated CH_4 emissions. Nevertheless, CH_4 emissions can remain high from former drainage ditches (Waddington & Price 2000). As bogs are generally nutrient poor and receive no fertilizer additions, nitrous oxide (N_2O) emissions are expected to be negligible. Nevertheless, nitrogen input from deposition has increased in the last decades in regions where peatlands are distributed in Europe (e.g. Northwest Germany, The Netherlands), which can lead to higher N_2O emissions, nowadays.

Different starting conditions have also to be considered regarding the restoration of peatlands formerly used for agriculture or forestry, e.g. type of land-use, degree and duration of drainage, peat type, depth and peat degradation, fertilization, liming, and forest productivity (here especially drainage by tree transpiration). For restoration of peatlands used for forestry two general pre-rewetting situations can be distinguished in Northern Europe. In the first, forest is only slightly drained with small hydrological effects. The land often forms imperfectly drained soils with great similarities to natural peatlands. Here restoration, e.g. rewetting, will cause only small changes. The nutrient cycling processes, including greenhouse gas fluxes, will fairly soon be similar to a natural peatland, low sedge fen or bog type (Kasimir-Klemedtsson *et al*., 1997). In the other case, forest drainage is more efficient and medium to high productive forests have developed. The decomposition of the peat after drainage is accelerated but, at the same time, a new humus layer of ca. 10 cm develops at the soil surface. Restoration, i.e. forest harvesting and rewetting, will raise the water table close to the surface. The peat decomposition will be reduced but at the same time the fairly easily decomposable humus layer and fine roots in the peat will be oxidized. Thus, an extra release of carbon will be observed during an initial restoration phase of 2-10 years before new wetland plants colonize. Finally, a medium to fairly species rich wetland will develop, quite different from the original peatland eco-system (Vasander *et al*., 2003).

Frequently, the structural, hydrological and chemical properties of peat layers remaining after agricultural and forestry use have been changed much more than those of peat layers remaining after peat extraction (Andersen *et al*., 2006; see also Chapter 3).

7.3. Greenhouse gas fluxes from cutover peatlands under restoration

7.3.1. Boreal peatlands in North America

Peat extraction in North America

Within North America approximately two-thirds of the peat extraction for horticultural purposes occurs within Canada and the demand for horticultural peat in Canada over the past century has led to the drainage and extraction of over 12 000 ha of peatlands (Cleary *et al*., 2005) of Canada’s estimated 171 million ha of peatlands (Gorham, 1991). Drainage and extraction of peatlands create conditions that disturb the natural hydrological and carbon cycling regimes of the ecosystem. Block-cutting and vacuum extraction techniques have been used primarily for the peat horticulture industry in Canada. Early peat horticulture was typically performed by block-cutting where drainage of the peatland occurred with a series of ditches and subsequent extraction trenches. The acrotelm was removed and discarded over the shoulder exposing the catotelmic peat used for horticulture. The extraction of this deeper peat was accomplished by hand-cutting into blocks on average to 60 cm depth (Girard *et al*., 2002) consequently leaving the landscape in an arrangement of alternating baulks (raised mounds) and trenches. The remaining acrotelm material discarded in the centre of the extracted trench was a form of unconscious plant reintroduction. Rarely used commercially today, remnants of these systems still remain in eastern North America. By the mid-1970s mechanized cutting became the dominant peat extraction practice for commercial use. Occurring at a larger areal scale than block cutting, deeper and more frequent drainage ditches are used in order to facilitate adequate drainage to support heavy extracting machinery. Similar to block-cutting, the acrotelm is removed; however, rather than discarded adjacent to the extraction site, the stripping spoil or skag (i.e. vegetation layer) is discarded completely. The peat surface is then milled to facilitate drying and peat fragments are typically vacuumed from the surface (i.e. vacuum extraction) using heavy tractors to depth of ~75 to 100 cm. Consequently, the peat extraction process creates unfavourable conditions at the peat surface especially for species such as *Sphagnum* moss, the main peat forming vegetation, to re-establish.

Greenhouse gas emissions from restored cutover peatlands

While studies have shown that decreased CO_2 efflux can occur due to rewetting of the surface, respiration can remain quite high post-restoration (Waddington & Warner, 2001). Waddington *et al*. (2003) also observed that the addition of mulch to the surface can represent a short-term source of atmospheric CO_2 due to its decomposition over time. New mulch decomposition accounted for between 17 and 30 % of total respiration. Similarly, Petrone & Waddington (2001) determined that a restored peatland was a larger source of CO_2 than an adjacent cutover site due to mulch decomposition exceeding the production of the newly emergent mosses and vascular vegetation. Mulch addition, blocking of ditches with old vegetation, and new emergent vegetation with plant reintroduction will also likely contribute to an increase of DOC leaching. In a restored peatland, DOC concentrations increased in the outflow, which is likely attributed to the wetter conditions post restoration (Waddington *et al*., 2007). However, while CO_2 fluxes may have increased post restoration (1753 g CO_2 m^{-2} yr^{-1}), DOC export represented only a small portion (0.7%) of the total CO_2 flux (Waddington *et al*., 2007) from the ecosystem. Additionally, restoration of peatlands leads to an increase in CH_4 production where fluxes can be significantly larger than cutover sites. It is suggested that a rise in water table and establishment of vascular vegetation post-restoration increases CH_4 flux due to increased labile carbon sources and enhanced CH_4 transport through the vegetation. An increase in CH_4 was observed from 0.02 g CH_4 m^{-2} yr^{-1} to 1.3 g CH_4 m^{-2} yr^{-1} three years post-restoration (Waddington & Day, 2007) representing over 70 times increase in CH_4 emissions. These findings are consistent with observations of natural peatlands being sources of atmospheric CH_4.

7.3.2. Boreal peatlands in Northern Europe

Peat accumulation at a self-regenerating cutover pit in Sweden

<u>Study site and methods</u>

Three boreal cutover peatlands where peat cutting by hand (peat pits, 20 x 100 m) had ended in the period 1950 - 1975 underwent a self-regeneration process (Box 7.1). The layer of the new formed peat was investigated 25-50 years after the end of peat cutting by sampling of undisturbed peat cores.

Box 7.1. Regenerating cutover peatland, Sweden

Site:

– Country:	SW Sweden
– Location:	Björnmossen bog
– Co-ordinates:	N 59°05’, E 14°39’

Climate:

– Precipitation:	800 mm yr^{-1}
– Evapotranspiration:	500 mm yr^{-1}
– Runoff:	300 mm yr^{-1}
– Annual mean temperature,:	+ 6 °C
– Vegetation period ($T > +5^{o}$C)	205 days

Peat properties:

– Peat type:	*Sphagnum* peat
– Climatic region	nemo-boreal bog

Former land use and restoration:

– Former land-use:	hand-cut peat pits, 20 x 100 m
– Abandoned since:	1950 / 1975
– Management type:	self-regeneration, poorly drained
– Investigation:	2000

Study methods:

– Peat accumulation determined using undisturbed peat cores

Reference: Lode, 2001

Results

The rate of peat accumulation varied between the sites with a low rate where 10 cm accumulated during 50 years giving 2 mm yr^{-1}, and a high rate at pits being under short regenerating period with 25 cm in 25 years resulting in a rate of 10 mm yr^{-1}. Using an average bulk density of 0.05 g cm^{-3} the organic matter accumulation could be estimated to 100-500 g m^{-2} y^{-1}. On the assumption of 20-50% of the biomass ending in peat (Ilomets, M., personal communication) the low rate would result in a peat accumulation of 20-50 g m^{-2} yr^{-1} while the high rate would result in 100-250 g m^{-2} yr^{-1}. With a carbon content roughly being 50% this would correspond to sinks in the range of -37 to -460 g CO_2 m^{-2} yr^{-1} (Lode, 2001). Methane and nitrous oxide emissions were not measured at this site.

Spontaneous regeneration of a cutover peatland in Finland

Study site and methods

Both Yli-Petäys *et al*. (2007) and Kivimäki *et al*. (in press) carried out studies in central Finland as part of the European RECIPE project (Boxes 7.2 & 7.3). Peat harvesting in the area started in 1942. The harvesting method used first was block-cutting, which created several 3 to 4 m deep trenches, surrounded by ca. 5 m wide dry baulks of peat. The harvesting was ceased in 1948 at the study site. The drainage system was fairly inefficient and the trenches started to regenerate spontaneously soon after the harvesting had ceased.

Box 7.2. Old self-regenerated cutover peatland, Finland

Site:

– Country:	Central Finland
– Location:	Aitoneva, Kihniö
– Co-ordinates:	N 62°12`, E 23°18`

Climate:

– Precipitation:	700 mm y^{-1}
– Annual mean temperature,:	+ 3.5 °C
– Vegetation period (T > +5^{o}C)	160 days
– Temperature sum (+5°C)	1100 d.d.

Peat properties:

– Peat type:	*Sphagnum* peat
– Climatic region	southern boreal to middle boreal

Vegetation:

- *Eriophorum vaginatum,. Carex lasiocarpa, C. rostrata, Sphagnum riparium, S. papillosum, S. pulchrum*

Former land use and restoration:

– Former land-use:	peat block cutting since 1942
– Abandoned since:	1948
– Management type:	self-regeneration, poorly drained
– Investigation:	2000-2001

Methods:

- Gas exchange measured with closed chambers
- Modelling of net ecosystem CO$_2$ exchange

Reference: Yli-Petäys *et al*., 2007

In the study of Yli-Petäys *et al*. (2007) sites of four regenerating plant communities were chosen for C flux measurements. The water table at the sites differed slightly. Instantaneous CO$_2$ exchange rates in the plots were determined using the closed chamber method described by Alm *et al*. (1997). Kivimäki *et al*. (in press) compared CO$_2$ dynamics in different vegetation types over 2 years (Box 7.3). They established altogether 19 sample plots in four types of patches along a moisture gradient at the site. Additionally, they laid out three bare control plots where they removed all vegetation. The seasonal CO$_2$ exchange was determined with the closed chamber method from June to September.

Results and discussion

In the study of Yli-Petäys *et al*. (2007) four plant communities revegetated the sites (average water table during growing season in cm below ground in parentheses): *Eriophorum vaginatum* and *Sphagnum riparium* ("Ripa": 12), *S. papillosum* ("Papi", 8), *Carex lasiocarpa, S. papillosum* and *S. pulcrum (*"PaPu": 4) or *Sphagnum pulcrum* ("Pulc": 2). All acted as sinks for CO$_2$ during the two growing seasons. Nevertheless, the CO$_2$ emission

Box 7.3. Actively restored cutover peatland, Finland

Site, climate and peat properties: (see Box 7.2)

Former land use and restoration:
- Former land-use: peat harvesting (Finnish HAKU harvesting method) until 1975 (Frilander et al. 1996)
- Restoration since: 1994
- Management type: blocking the ditches, additional water supply
- Investigation: 2003-2004

Vegetation:
- monostands *Eriophorum vaginatum*
- monostands *Carex rostrata*
- mixed stands *Eriophorum vaginatum* and *Sphagnum*
- mixed stands *Carex rostrata* and *Sphagnum*
- bare plots

Methods:
- Gas exchange measured with closed chambers
- Modelling of net ecosystem CO_2 exchange

Reference: Kivimäki *et al*., in press

during winter was in most cases as high as the CO_2 uptake during the growing season. Thus, the estimated one-year net CO_2-C balance was low or even clearly negative and amounted to mean values of 35, 31, 53 kg CO_2 m^{-2} yr^{-1} in the “Ripa”, “Papi” and “PaPu” communities for the two years of the study. Only in the “Pulc” community, which had the highest water table, a net mean carbon dioxide uptake of -143 kg CO_2 m^{-2} yr^{-1} was observed. Thus, the low seasonal production of most plant communities in this study was not sufficient to exceed losses of winter time respiration, which may partly result from suboptimal weather conditions during the study period.

Likewise, pristine mires may also undergo large interannual variations in CO_2 balance (e.g. Alm *et al*. 1999a,). Unlike in the studies of Bortoluzzi *et al*. (2006) from Central Europe, the advanced regeneration stage in Aitoneva did not represent a strong sink of CO_2. Besides weather conditions it is also possible that the residual peat decomposition in general exceeds the production rate of new biomass of the trenches. The results of Yli-Petäys *et al.* (2007) may suggest decreased carbon sink of restored site after the observed *Eriophorum* peak in productivity (Tuittila *et al*., 1999). Methane emissions were high in treatments with high water table and amounted to 19, 29, 36 and 45 kg CH_4 m^{-2} yr^{-1} in the “Ripa”, “Papi”, “PaPu” and “Pulc” plots.

Kivimäki *et al*. (in press) studied the carbon dioxide exchange of four vegetations types (mean water table in cm in parentheses, negative values mean water table above ground): monostands of *Eriophorum vaginatum* (“EV”: 0) or *Carex rostrata* (“CR”: -3) and mixed stands of *Eriophorum* or *Carex* with *Sphagnum* (“EV+S” and “CR+S”: -10). A bare control had a mean water table of 7 cm below ground. The seasonal net CO_2 exchange resulted in a carbon uptake of the peatland both years in all the vegetated plots. Assuming a CO_2 emission of 161 g CO_2 m^{-2} outside the growing season (Yli-Petäys *et al*., 2007), the annual net ecosystem exchange (NEE) was calculated. Mean values amount to -97 and -63 g CO_2 m^{-2} y^{-1} in the monostands "EV" and "CR", respectively, and to -347 and -293 g CO_2 m^{-2} y^{-1} in the mixed stands "EV+S" and "CR+S", respectively. The interannual variation of the mean water table and the slight moisture gradient had no significant effect on the CO_2 exchange. The plots with *Sphagnum* had higher seasonal NEE than the pure sedge plots resulting from the higher seasonal gross productivity (GEP). It thus seems that increased number of species leads to increased productivity and either vascular plants become more efficient when growing with *Sphagnum* or *Sphagnum* becomes more efficient when growing with vascular plants.

The bare peat plots were seasonal sources of 123 g CO_2 m^{-2} into the atmosphere. Alm *et al*. (1999b) estimated that CO_2 release from peat in winter would represent 21 to 23 % of the annual total CO_2 release from peat. Thus, the bare plots emitted 150 g CO_2 m^{-2} yr^{-1}. These values were much smaller than those measured by Waddington *et al*. (2002) from non-restored cut-away peatland. They had values of 1331 g CO_2 m^{-2} y^{-1} in dry year and 411 g CO_2 m^{-2} yr^{-1} in a rainy year. It seems that the restoration has also decreased the respiration of the non-vegetated areas at Aitoneva. By colonization by *Sphagnum* and vascular plants, the respiration of the bare peat surface decreases and with the growing functional diversity the ecosystem becomes more efficient in carbon accumulation. Because different *Sphagnum* species are favoured by different water levels, their species richness enhances the forming of *Sphagnum* coverage to the whole area. Spreading *Sphagnum* diaspores by the North American method (Quinty & Rochefort, 2003) may further speed up this process.

7.3.3. Temperate peatlands in Central and Western Europe

Rewetting of hand-cut bog peat pits in the Netherlands

The Fochtelooërveen area is a disturbed raised bog in the north of the Netherlands (Nieveen *et al*., 1998; Box 7.4). The vegetation is natural tussock grassland, with an averaged height of approximately 40 cm. A layer of 10 cm of dead organic material from the previous growing seasons covered the tussocks and the hollows in between. The dominating plant species is *Molina caerulea* (>75%) but also species like *Eriophorum vaginatum*, *Calluna vulgaris* and *Erica tetralix* could be found. Throughout the seasons, the water table varied, depending on the weather, from 0 to 20 cm below the tussock soil interface but the soil remained saturated. CO_2 flux measurements were conducted, using the eddy correlation technique, during June 1994 and October 1995. For this period the site acted as a source of CO_2. Total NEE was estimated at 97 g CO_2 m^{-2} yr^{-1}.

Restoration of a rewetted industrial cutaway peatland in Ireland

Study site

The study was carried out in an Irish rewetted industrial cutaway peatland (Wilson *et al*., 2007; Box 7.5). Turraun was one of the first bogs to undergo industrial peat extraction in Ireland. Prior to harvesting, the average depth of peat at Turraun was 6.2 m (Rowlands, 2001). When milled peat harvesting ceased in the 1970s, the residual peat depth ranged from 0 - 1.8 m. Over the following decades, the cutaway area was allowed to revegetate naturally. In 1991, a 60 ha lake was constructed, the drainage ditches

Box 7.4. Rewetting of a hand-cut bog, the Netherlands

Site:

– Country:	NE Netherlands
– Location:	Fochtelooër bog
– Co-ordinates:	N 53°00’, W 6°23’

Climate:

– Precipitation:	853 mm y^{-1}
– Evapotranspiration:	531 mm y^{-1}
– Runoff:	n.a.
– Annual mean temperature,:	+ 9.0 °C
– Vegetation period (T > +5°C)	264 days

Peat properties

– Peat type:	*Sphagnum* peat
– Climatic region	mid-latitude marine

Former land use and restoration:

– Former land-use:	hand-cut peat pits
– Restoration since:	1985
– Management type:	damming
– Investigation:	1994/1995

Methods:

- Eddy correlation technique

Reference: Nieveen *et al*., 1998

were blocked, a mineral soil/peat bund was formed and the cutaway area was reflooded. Since that time, a wide range of vegetation communities have become established representing both dryland and wetland ecosystems. The dryland communities are dominated by *Betula* and *Salix* spp., *Calluna vulgaris*, *Molinea caerulea*, and *Juncus effusus*. Within the wetlands a hydroseral gradient, i.e. the sequence of vegetation communities which occur during the transition from shallow open water at the edge of the lake to drier terrestrial ecosystems, has developed. These include extensive stands of *Phragmites australis*, *Typha latifolia*, *Phalaris arundinacea*, *Eriophorum angustifolium* and *Carex rostrata* communities.

The residual peat deposit is mainly *Phragmites australis* or fen type peat overlying undulating calcareous marl or clay sub-peat mineral soils or limestone bedrock. There is a range in pH values from 4.5 to 7.9 at Turraun closely related to the depth of the underlying calcareous sub-stratum (Rowlands, 2001). Bulk density values range from 180 ± 48 kg m^{-3} (0 – 15 cm peat depth), 120 ± 7 kg m^{-3} (15 – 30 cm) and 120 ± 11 kg m^{-3} (30 – 45 cm).

From the different communities that revegetated the site, four wetland communities were selected for C flux measurements called after the dominating plant species: *Typha (T. latifolia); Phalaris (P. arundinacea)*, *Eriophorum/Carex (E.*

Box 7.5. Rewetted industrial cutaway peatland, Ireland

Site:

– Country:	Irish Midlands
– Location:	Turraun, Co. Offaly
– Co-ordinates:	N 53º14' - 53º19', W 7º42' - 7º48'

Climate:

– Precipitation:	804 mm yr^{-1}
– Annual mean temperature:	+ 7.5 °C

Peat properties:

– Peat type:	fen (*Phragmites australis*) over calcareous fen-peat
– Climatic region	temperate, marine

Former land use and restoration:

– Former land-use:	milled peat harvesting
– Restoration since:	1970
– Restoration type:	re-vegetating naturally 1991: blocking of ditches
– Investigation:	Jan. 2002- Dec. 2003

Methods:

- Gas exchange measured with closed chambers
- Modelling of net ecosystem CO_2 exchange

Reference: Wilson *et al*., 2007

angustifolium and *C. rostrata)* and *Juncus/Holcus (J. effusus and H. lanatus).*

Gas exchange measurements and balances

CO_2 fluxes were measured between April 2002 and December 2003 using the closed chamber method with light and dark chambers. CH_4 measurements took place between July 2002 and December 2003. The hourly time series of environmental variables recorded by a weather station and data loggers located within the communities were used to reconstruct the annual gas balances for each sample plot separately (Figure 7.1).

Results

All communities were sources of CO_2 and CH_4 in 2002 and 2003 (Figure 7.1). Large losses of CO_2 occurred in all communities driven partly by considerable losses during the wintertime periods (Wilson *et al*., 2007) and also by deeper water tables throughout the peatland in 2003. Emissions of CH_4 were highest in the *Typha* communities in both years. No CH_4 fluxes were detected in either the *Juncus*/*Holcus* communities or in the bare peat plots as a consequence of deep water tables (*Juncus*/*Holcus*) or absence of vegetation (bare peat plots).

Conclusions

Restoration of the C sink function at Turraun was not observed in the two years of the study. Interannual variation in climatic inputs had a significant impact on

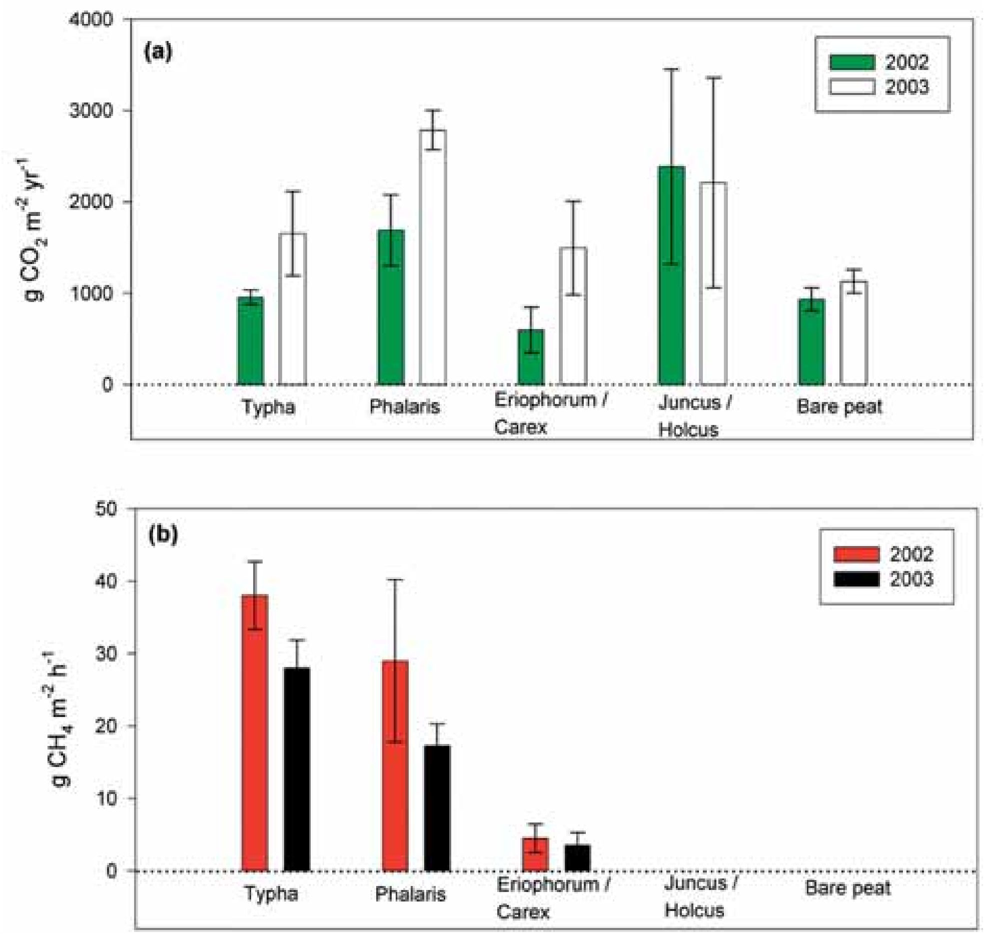

Figure 7.1. *Annual (a) Net ecosystem exchange of CO_2 (g CO_2 m^{-2} yr^{-1}) and (b) CH_4 fluxes (g CH_4 m^{-2} yr^{-1}) for 2002 and 2003 at Turraun, Co. Offaly. For more details see Box 7.5.*

water tables within the peatland resulting in large losses of CO_2 particularly in late summer / early autumn of 2003. Without a functioning acrotelm layer, it is difficulty for a cutaway peatland to maintain a high water table and large losses of CO_2 may be inevitable. Furthermore, the mild, oceanic climatic conditions experienced in Ireland permit the degradation of organic matter even throughout the winter period.

7.4. Greenhouse gas fluxes from restored peatlands formerly under forest, agricultural use or drained fallow land

7.4.1. Boreal bogs and fens in Northern Europe

Estimation of greenhouse gas emissions from Scandinavian bogs and fens
Information on gas fluxes from Scandinavian restored sites where no peat excavation had taken place and which have been under forest or agricultural use before

is limited. If no peat has been excavated and if the sites have only weakly been drained or fertilized for the past land-use, gas exchange from the restored sites should soon reach the level of natural mires after restoration. Therefore, here some results of Scandinavian studies on greenhouse gas exchange from pristine peatlands are shown.

For poor sites, such as bogs, values up to -367 g CO_2 m^{-2} yr^{-1} have been reported, while fens are in the lower range, i.e. ca. -55 g CO_2-C m^{-2} yr^{-1} (Tolonen & Turunen, 1996). For CH_4 emissions from natural mires a most comprehensive investigation was carried out on a large number of peatlands in Sweden, however mainly during one year (Nilsson *et al*., 2001). The CH_4 emission values were stratified on three trophy (nutrient) levels from poor to rich and also for geographical location. The values are presented here for the poor and rich sites together with the range of the emission values. The poor sites mainly bogs show a range of 1.3 to 10.7 g CH_4 m^{-2} yr^{-1}. The richer sites being sedge fens are in the range of 4 to 22.7 g CH_4 m^{-2} yr^{-1}, tall sedge fens having the highest values.

The N_2O emissions from pristine peatlands are very low. Values do not differ between poor and rich sites. At investigations on two sites, a range of 0.02 to 0.03 g N_2O m^{-2} yr^{-1} was found (von Arnold, 2004). With high nitrate availability, e.g. on formerly fertilized peatlands, the values could reach higher levels.

The global warming potential calculated from CO_2 accumulation, CH_4 and N_2O emissions result in a sink of -354 to -283 g CO_2 equivalents (CO_2-e) m^{-2} yr^{-1} for poor sites, while richer sites tend to result in a source of -20 to 122 g CO_2-e m^{-2} yr^{-1} (global warming potential on a 500-year-basis; see Chapter 5 for more details).

Calculations and compilation of data from Swedish rewetted forested peatland show both C sequestration and CO_2 emission after rewetting (Nilsson & Nilsson, 2004). On poor sites, C sequestration is observed (-294 g CO_2-e m^{-2} yr^{-1}). This is due to a relatively high accumulation rate and a low decomposition rate. But, with time the accumulation rate might decrease. Methane emissions are low (3 g CH_4 m^{-2} yr^{-1}). On rich sites, on one hand, the sequestration rate is lower than on poor sites amounting to -110 g CO_2 m^{-2} yr^{-1}. On the other hand, high CH_4 emissions occur. The latter are estimated as 27 g CH_4 m^{-2} yr^{-1}. N_2O emissions from rewetted sites are negligible. The loss of C stored in tree biomass is not included in this calculation. In summary, rich peatlands are about neutral with respect to greenhouse gas emissions while poor sites are generally sinks.

7.4.2. Boreal and temperate peatlands in Eastern Europe

Rewetting experiments in Eastern Germany

Study site

The experimental site is a part of the Peene river valley mire in Northeast Germany (Box 7.6). It is situated within a large-scale nature conservation project called "Peene-Haffmoor / Peenetal" (20 000 ha). It is a fen mire, partially of the percolation mire type and partially of the spring mire type. Total peat depth is up to 10 m. The carbon: nitrogen (C/N) ratio and peat degradation according to von Post are 12.2 and 10 in 0-20 cm, 18.5 and 6 in 20-50 cm, and 21.4 and 3 in 50-110 cm, respectively.

There has been low-intensity use for pasture and local peat cutting since the middle of 18th century. After 1960 deep drainage and periodic ploughing with renewal of the grass sward was carried out to ensure an intensive use as grassland. In 1990 the intensive land-use was abandoned.

Box 7.6. Restoration of grassland fens, NE Germany

Site:	
– Country:	NE Germany
– Location:	Zarnekow Polder
– Co-ordinates:	N 53°52´ E 12°53´
Climate:	
– Precipitation:	544 mm y^{-1}
– Annual mean temperature:	+ 8.1 °C
– Vegetation period (T > +5°C):	222 days
Peat properties:	
– Peat type:	fen (percolation or spring fen)
– Climatic region	cool, temperate
Former land use and restoration:	
– Former land-use:	intensive grassland since 1960
– Restoration since:	2005
– Restoration type:	a.) low intensity pasture b.) flooding (0.2-1 m) in 2005
– Investigation:	April 2004 until 2007

Methods:

- Gas exchange measured with closed chambers
- Partially automated chambers

References: Augustin & Joosten, 2007; Augustin, unpublished

One part of the polder area was used for low-intensity pasture. The other part was flooded again in the course of the restoration project in the beginning of 2005.

The water level varies between 20 and 100 cm above surface on the flooded area. At the non-flooded low intensity grassland the groundwater level is at soil surface during winter time and up to 60 cm below surface during summer. The hydrologic regime is influenced in a complex way both by the river Peene which has a very small slope before flowing into the Baltic Sea and by the groundwater of the adjacent valley edges.

The restoration was started by opening the dykes which limit the river Peene. Since the water level of the river is higher than a part of the fen area today, as a result of the peat decline, it was flooded after dyke opening. Two treatments were established: recently rewetted low-intensity grassland (control) and recently flooded grassland (Joosten & Augustin, 2006; Augustin & Joosten, 2007; Augustin, unpublished).

Results

Opening of the dykes resulted in changes in the gas exchange on both the flooded area and the rewetted grassland because of the risen groundwater level. Contrary to the originally drained sites the rewetted grassland (control) is a weak source of N_2O (0.22 g N_2O m^{-2} yr^{-1}) and CH_4 (0.001 g CH_4 m^{-2} yr^{-1}). Completely surprising is that the rewetted grassland already functions as a strong CO_2 sink, too (-917 g CO_2 m^{-2} yr^{-1}). On the flooded site the sink function for CO_2 was also established very rapidly and in a very strong manner (-2383 g CO_2 m^{-2} yr^{-1}). Simultaneously, however, extremely high methane emissions of, up to 267 g CH_4 m^{-2} y^{-1} occurred. The N_2O release was lower than in the rewetted grassland.

In the first year after flooding the treatments behaved contrary to the expectations. In a 500 year perspective the control showed a strongly positive climate effect or GWP (-883 g CO_2-e m^{-2} yr^{-1}). Despite the high CO_2 assimilation the flooded treatment had a smaller GWP than the non-flooded rewetted grassland due to the high CH_4 emission (-352 g CO_2-e m^{-2} y^{-1}). The high CH_4 emission in the flooded treatment is due to the fact that fresh and easily degradable plant material is submerged and a fermentation process is initiated by flooding.

Conclusions

Information from literature and observations indicate that after flooding of degraded fen mires three phases with very different characteristics may occur. In the *first phase* extremely high CH_4 emissions will be observed in connection with a low net CO_2 uptake (accumulation). This initial phase has an extremely negative climate effect. The experiments discussed above are presently in this phase. In the *second phase*, CH_4 emissions are strongly reduced, whereas CO_2 uptake shows its maximum. This phase has a slightly positive climate effect. For the final *third phase* both low CH_4 releases and low net CO_2 uptakes are expected, similar to the situation in pristine mires. In this phase the climate effect of a rewetted peatland is close to that of a natural one.

Regretfully no information exists on the duration of the individual phases and how emissions develop within and between the phases. Moreover, there is only little known about the effect of different water levels after flooding on the gas exchange. Therefore comprehensive long-term field studies on gas fluxes are urgently needed for designing optimally effective methods and to evaluate the effects of flooding.

7.4.3. Temperate bogs in Central and Western Europe

Restoration of drained South German bogs under fallow

Study site

The Kendlmühlfilze is a representative bog area for this extensive mire belt (Box 7.7). Total peat depth is up to 10 m, with fen peat in the lower 3 m and bog peat in the top 7 m. The C/N ratio of the upper peat layer was between 26.5 (restored former drained sites) and 40.5 (natural *Sphagnum* hollow).

Former land-use at the studied sites was fallow land under drainage as preparation for peat cutting (but without extraction of the peat) and small-scale domestic peat cutting. Both activities ceased around 1950. Restoration works were undertaken in 1990 and 1999. Therefore, two time steps could be included in the assessment of the restoration effect on greenhouse gas exchange. The gradient from natural to restored to degraded sites is reflected in the mean water table. Natural sites show water tables between 0 and 10 cm, degraded sites between 12 and 29 cm and restored sites between 5 and 12 cm below surface. Maximum oscillation could by found at the degraded sites (54 cm) and minimum at the natural sites (17 cm).

Restoration included blocking the ditches (former drained areas) and damming (former peat cut areas) to reduce the discharge from the sites. Drained sites where small-scale peat cutting had taken place were (partly) flooded whereas drained sites without peat cutting were just rewetted. No active introduction of

Box 7.7. Rewetting of bogs drained for domestic peat-cutting, South Germany

Site:

– Country:	S Germany
– Location:	Kendlmühlfilze
– Co-ordinates:	N 47°20´ E 12°25´

Climate:

– Precipitation:	1483 mm y^{-1}
– Annual mean temperature:	+ 8.3 °C

Peat properties:

– Peat type:	bog
– Climatic region:	cool, temperate

Former land use and restoration:

– Former land-use:	fallow land, drained for peat cutting , no or domestic peat cutting until 1950
– Restoration since:	a) 1990, b) 1999
– Management type:	blocking of ditches and damming
– Investigation:	1999 – 2000

Methods:

- Gas exchange measured with closed chambers
- Modelling of net ecosystem CO_2 exchange

Reference: Drösler, 2005

vegetation was undertaken. Natural versus restored versus degraded (drained only and peat cut) sites were compared.

Results

Degraded former peat cut sites had CO_2 emission of 1472 g CO_2 m^{-2} yr^{-1}, degraded drained sites without peat cutting showed lower losses of 864 g CO_2 m^{-2} yr^{-1}. Restored sites had emissions of 466 g CO_2 m^{-2} yr^{-1}. Only the natural sites had a significant uptake with a mean CO_2 sink rate of -260 g CO_2 m^{-2} yr^{-1}. Methane emissions at the former peat cut sites were insignificant (0.07 g CH_4 m^{-2} yr^{-1}), whereas at the drained but not peat cut sites, emissions were moderate at 1.9 g CH_4 m^{-2} yr^{-1}. The restored sites showed higher emissions of 4.8 g CH_4 m^{-2} yr^{-1}. As expected, the highest emissions were found at the natural sites with a mean of 25.9 g CH_4 m^{-2} yr^{-1}. Nitrous oxide emissions were only significant at the former peat cut sites with a mean of 0.17 mg N_2O m^{-2} yr^{-1}. Looking at the C balance, calculated as the difference between NEE, CH_4-C losses and estimated DOC losses, the mean at the natural sites was -45.6 g C m^{-2} yr^{-1}, which is around the double of the long-term rate of carbon accumulation for northern bogs.

As shown, natural bogs in this study are sequestering C. However, for the assessment of the climatic relevance, the global warming potential (GWP) is the key indicator and is presented here on the 500 year perspective. Degraded former peat cut sites had a GWP of 1499 g CO_2-e m^{-2} yr^{-1}, respectively. Drained but not peat cut sites showed 878 g CO_2-e m^{-2} yr^{-1}. At the restored sites, the GWP was estimated to be 502 g CO_2-e m^{-2} yr^{-1}. Only natural sites act as a sink for the greenhouse gases at the long term (500 years) perspective with GWP of -67 g CO_2-e m^{-2} yr^{-1}.

Conclusions

Rewetting of temperate peat bogs is shown to reduce C losses in comparison to drained bog sites. However, restoration does not immediately lead to a C sink within the studied first ten years. But, it helps to reduce C losses significantly. Natural sites were the only ones showing C uptake in this study. Restoration of peat bogs for climate mitigation should avoid flooding the sites but instead should establish a water table slightly below peat surface to reduce the dominating effect of CH_4 emissions. As the peat bogs along the Alps are no longer under land use pressure, restoration can be seen from a functional aspect, not provoking too many conflicts with the land-owners. Conflicts between the objectives of climate mitigation and species protection are not prominent. The typical peat bog species have evolved under natural conditions which are favourable in terms of greenhouse gas exchange.

7.4.4. Temperate fens in Central and Western Europe

Restoration of a previously drained fen area in the Netherlands

Study site and methods

The village Zegveld is located in the centre of the peat area in the Western part of the Netherlands (Box 7.8) (Langeveld *et al*., 1997). The cultivation of the area around the Zegveld started in the 11th century. Drainage by digging ditches was the main measure to enable the mining of peat. This resulted in a typical landscape with long stretches of land and numerous ditches.

Box 7.8. Relict of a previously drained partly restored fen area, the Netherlands

Site:	
– Country:	SW Netherlands
– Location:	Zegveld
– Co-ordinates:	N 52°07’, E 4°51’
Climate:	
– Precipitation:	790 mm y^{-1}
– Evapotranspiration:	543 mm y^{-1}
– Annual mean temperature,:	+ 9.8 °C
– Vegetation period ($T > +5^oC$)	280 days
Peat properties:	
– Peat type:	fen (woody sedge)
– Climatic region	temperate, marine
Former land use and restoration:	
– Former land-use:	grassland
– Restoration since:	1970
– Management type:	raising of water table
– Investigation:	2001/2002

Reference: Langeveld *et al*., (1997)

After the peat mining stopped, a 5-6 m thick peat layer remained. The main land use type became production grassland with interchanging periods of grazing by cows or sheep and mowing. The water content of the soil is regulated by maintaining the water levels in the ditches at a fixed height. The traditional depth of the water table in the ditches is 70 to 90 cm below the surface. The consequence is a subsidence rate of approximately 1.1 cm yr^{-1} of the land surface (Beuving & van den Akker, 1996). In the early 1970s an experiment was started to investigate possibilities to reduce the rate of subsidence by manipulating the water table depth. At a research farm near Zegveld, two water table regimes were maintained for a number of fields. The first water table regime was identical to the traditional regime, i.e. 70 cm below the surface (hereafter called “dry” treatment), and the second regime was 20 cm below the surface (hereafter called “wet” treatment). This resulted in water table depths in the centre of the fields varying between -15 cm in winter and -60 cm in summer for the dry, and for the wet treatment between 0 and -35 cm.

To estimate the effect on the greenhouse gas emissions of this difference in water table depth, measurements of CO_2 and N_2O exchange were performed simultaneously on both fields. Based on earlier work by van den Pol-van Dasselaar *et al*. (1999) it was assumed that for these water table depths the emission of CH_4 is negligible. For the measurement of CO_2 exchange the eddy correlation technique was applied. N_2O emissions were measured at irregular time intervals (varying from 1 week during the growing season to 1 month in winter).

Results and conclusions

In both treatments there is a net emission of CO_2, where the wet plot showed a 25 % lower emission than the dry plot (Fig; Jacobs *et al*., 2003). The emission of N_2O was approximately 34 % lower for the wet relative to the dry treatment.

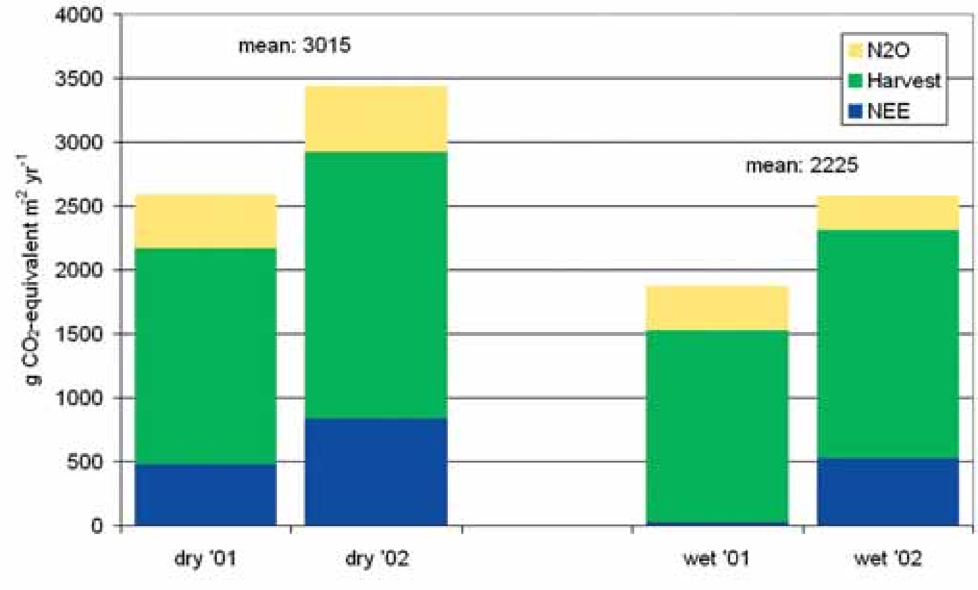

Figure 7.2. *The total emission of CO_2 and N_2O for the dry and the wet fields of partially restored peatland in the Netherlands following use as grassland. For more details about the study site see Box 7.8.*

Emission of N_2O is very much governed by management, i.e. the timing and amount of fertilizer used and the grazing density. However, this did not explain the differences found. The total amount of fertilizer and manure applied was 15 % higher at the wet field. A more likely explanation is the higher water table of the wet field limiting the aeration of the top soil and thus stimulating the production of nitrogen gas (N_2) at the expense of N_2O (see also Chapter 3). Data were lacking in this experiment to verify this hypothesis. In addition to NEE measured with the eddy correlation system, losses of C in biomass removed by mowing or grazing were taken into account. In Figure 7.2 the greenhouse gas balance of the fields is depicted as the sum of NEE, the biomass removed and the emission of N_2O. This shows that the total emission is 26 % less for the wet treatment than for the dry treatment, i.e. 2225 versus 3015 g CO_2-e m^{-2} yr^{-1}.

To evaluate the net effect of land use of an area on the total emission of greenhouse gases other sources of emission should be taken into account as well. For the experiment discussed above, other possible contributions exist which were not quantified, e.g. the outflow of carbon by hydrological pathways and, at the farm level, the emission from the stables and the fuel used to manage the land. More information of emissions at the farm level for this site may be found in Langeveld *et al*. (1997).

Most of the peat areas in the Netherlands are traditionally in agricultural use, mainly as grassland. There is still a lot of debate about the future land-use for this area. If land subsidence and CO_2 emissions are to be stopped, the water table should be even higher than as described above for the wet treatment. This would make the traditional concept of agriculture impossible in this area. At the moment the most likely solution is a limited raising of the water table for a large area and a water table close to the surface only for small areas. At present, possible benefits of a higher groundwater table in summer by applying subsurface-infiltration using drains are being investigated. Also, research into possible negative side effects on CH_4 emissions in the case of a groundwater table at or close to the surface is being performed.

Results of a rewetting experiment on a shallow grassland fen in northwest Germany

Study site

A rewetting experiment on a fen was carried out in northwest Germany in the Dümmer region (Meyer *et al*., 2001; Box 7.9). The experiment was part of a nation-wide project on rewetting of fens. The fen is of lacustrine origin (in the vicinity of the Dümmer Lake). A *Phragmites australis*, small sedge or brook forest peat layer of 30 to 60 cm overlies 30 cm of calcareous, clay or organic mud. The pH value (measured in $CaCl_2$) in the peat layer ranges from 4.5 to 5.3. The bulk density is about 480 kg m^{-3} (0 – 30 cm peat depth) and 200 kg m^{-3} (30 – 55 cm). The ratio of organic carbon to total nitrogen (C/N ratio) varies between 14 and 18.

Experimental design

The site had been used as intensively fertilized grassland until 1992. In 1993 fertilization was stopped, but harvesting was continued once to three times a year, if possible.

The following treatments were established:
1. *Non-rewetted (dry):* In this treatment no change in water regime was done. The mean water table was 50 and 30 cm below the surface in the winter months (November to April) and 80 and 70 cm below the surface in the summer months (May to October), in the years 1996 and 1997, respectively, where the gas measurements were carried out. The grassland was not

Box 7.9. Rewetting of a shallow grassland fen, NW Germany

Site:	
– Country:	NW Germany
– Location:	Dümmer
– Co-ordinates:	N 52º47', E 8º30'
Climate:	
– Precipitation:	698 mm yr^{-1}
– Annual mean temperature:	+ 8.7 °C
Peat properties:	
– Peat type:	fen (*Phragmites australis*, sedge, wood), lacustrine origin
– Climatic region	temperate
Former land use and restoration:	
– Former land-use:	intensive grassland
– Restoration since:	1993
– Management type:	no fertilization, a) rewetting with ditches, b) flooding
– Investigation:	1996 and 1997

Reference: Meyer *et al*., 2001

fertilised and harvested twice a year. The grassland vegetation is dominated by *Phalaris arundinaceae, Poa pratensis* and *Alopecurus pratensis*.

2. *Rewetted by ditches (moist):* In 1993, a 2.5 ha fen area was rewetted by ditches which had been dug at a distance of 40 m. The water level in the ditches was maintained constant at 30 cm below the surface through the year by supplying river water from the nearby Hunte River. The mean water table was observed at 35 and 15 cm below the surface in the winter months and at 50 and 50 cm below the surface in the summer months, in the years 1996 and 1997, respectively. 347 mm and 357 mm of river water had been pumped into the rewetted area in the years 1996 and 1997, respectively.

3. *Rewetted by flooding (flooded):* In 1995, another area of 2.5 ha was rewetted by flooding with water from the Hunte River at 10 cm above ground level during the whole year. Vegetation changed from the formerly dominating species *Phalaris arundinaceae* and *Deschampsia cespitosa* to increasing spread *of Glyceria fluitans* and *Typha latifolia.* Harvesting was not possible anymore.

Twelve plots were established on each treatment, six with and six without vegetation. Plots with vegetation were used to measure the gas exchange of N_2O and CH_4. Plots without vegetation, where the vegetation had been eliminated in the beginning by taking off the upper 2 cm layer and was eliminated during the experiment by burning upcoming plants, were designated to determine CO_2 emission from the peat. Gas measurements were done weekly between March 1996 and March 1998 using the closed chamber technique.

Results

All plots were sources of CO_2 independently of the rewetting measure (Figure 7.3a). Under flooding the highest emissions were observed in the first two years after the beginning of the experiment. The dry and moist treatment behaved almost neutral with respect to CH_4 emissions. On the contrary, flooding lead to high CH_4 emissions of 61 to 131 g CH_4 m^{-2} yr^{-1} (Figure 7.3b). The N_2O emissions were slightly higher in the moist plot compared to the dry treatment (Figure 7.3c). In the flooded treatment, N_2O emissions were reduced to 0 and even a small sink function for N_2O was observed.

Conclusions

Raising the water table by ditches which are filled 30 cm below surface did not reduce the CO_2 emissions of the fen and even slightly increased the N_2O emissions by favouring nitrogen mineralisation and denitrification due to higher moisture contents. Thus, this measure, designed to rewet under continuing land-use as grassland, is not suited to reduce greenhouse gas emissions and peat mineralisation. The underlying mud impedes water rise from the sandy subsoil and, thus, in summer the water table falls in the plots between the ditches due to high water consumption by transpiration.

Also, flooding did not restore the function of the fen as a C sink in the first two years. Even though not the entire NEE was assessed, it can be concluded from the CO_2 emissions from the bare plots, that flooding lead to high C emissions from aerobic and anaerobic processes. Only the N_2O emission was strongly reduced and the site converted into a net N_2O sink. Nevertheless, the flooding seems to be the best method, to keep water on the plots during the whole year, and vegetation changes indicate a shift towards peat forming plants (*Typha latifolia*, *Phragmites australis*). New field measurements planned for the coming years are designed to show a decrease in CO_2 emissions from the flooded site. It is yet unclear, whether in this highly degraded peat a C sink function will be re-established one day.

7.5. Conclusions on the most efficient restoration techniques with respect to greenhouse gas emissions and/or peat growth

The results presented in this chapter are summarized in Table 7.1. There is a large variation in greenhouse gas emissions between the different restored peatland sites. The emissions of CO_2, CH_4 and N_2O and the C accumulation rate depend on the geographical situation (i.e. temperate vs. boreal peatlands) and peat type (i.e. nutrient poor bogs vs. nutrient rich fens).

Most investigations of gas emissions are from North European bogs. The global warming potential greenhouse gas emissions from Finnish or Swedish spontaneously regenerated cutover bogs or bogs used for agriculture or forestry is slightly negative to neutral, covering a range between -354 g CO_2-e m^{-2} yr^{-1} (sink of greenhouse gases) and 253 g CO_2-e m^{-2} yr^{-1} (source of greenhouse gases) on a 500 year basis. Nevertheless, information on CH_4 emissions is sometimes missing and could worsen the GWP by 10 to 81 g CO_2-e m^{-2} y^{-1} (Nilsson *et al*., 2001).

North European fens tend to show gas emissions with a positive global warming potential due to lower C accumulation and higher CH_4 emissions than the bogs. The GWP is in the range of -20 to 122 g CO_2-e m^{-2} yr^{-1} (500 years).

Restored Canadian cutover bogs show exceptionally high gas emissions, especially

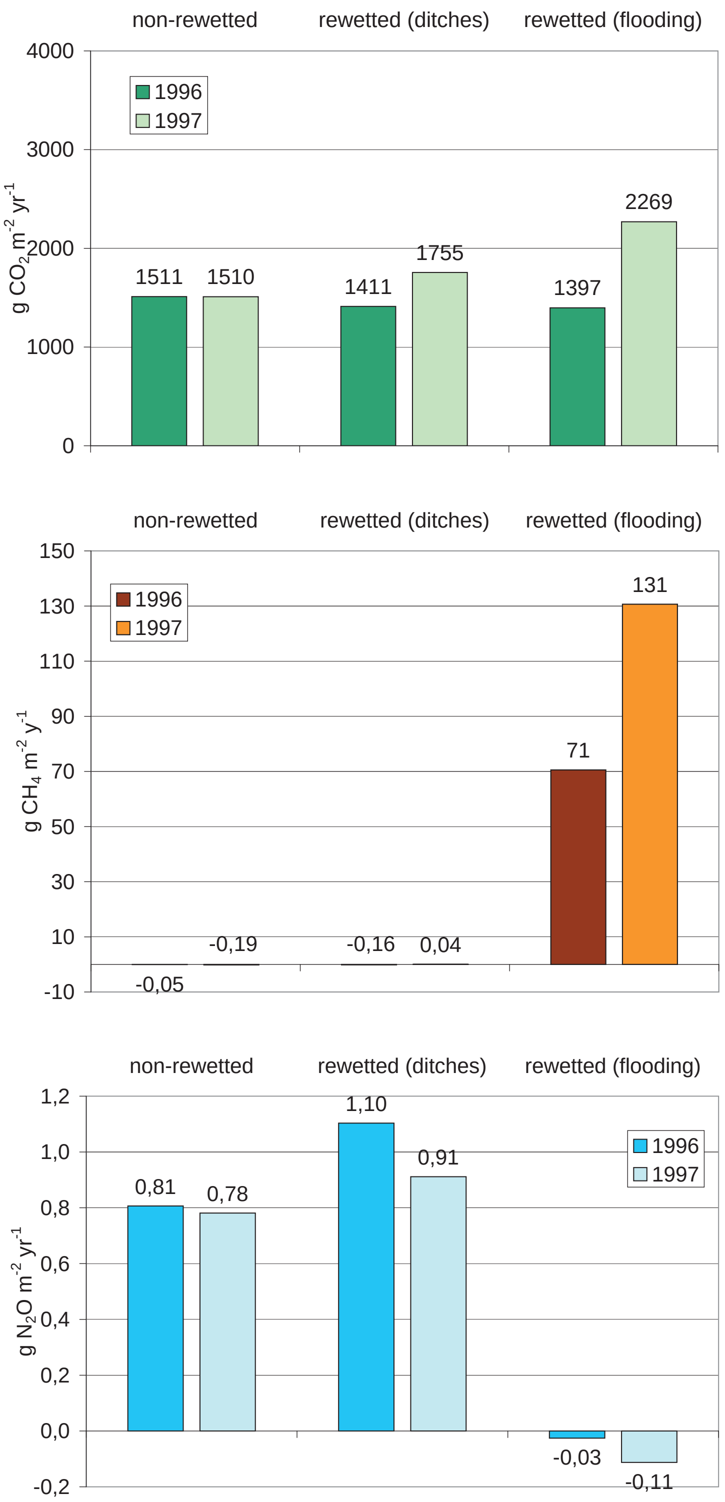

Figure 7.3. *Annual (a) CO_2 fluxes from bare plots; (b) CH_4 fluxes and (c) N_2O fluxes from vegetated plots for 1996 and 1997 from a shallow fen at Schäferhof, Hunte, Germany.*

Table 7.1. *Greenhouse Gas Emissions from Restored and Non-restored (control) Sites of Different Peat Types, Regions and Restoration Types*

Country	precip/ temp (mm yr^{-1}/ °C)	Restoration type, vegetation	Time after restoration (yr)	NEE (CO_2) (gCO_2 m^{-2} yr^{-1})	CH_4 (gCH_4 m^{-2} yr^{-1})	N_2O (gN_2O m^{-2} yr^{-1})	GWP[a] 100 yr (gCO_2-e m^{-2} yr^{-1})	GWP[a] 500 yr (gCO_2-e m^{-2} yr^{-1})	References
Cutover bogs (see section 7.2)									
Boreal									
Canada		Blocking of ditches, mulching with straw	3	1753[b]	1,3	0	1785	1763	Waddington *et al*., 2002
		Peat cutting area, non-restored		871	0,02	0	871	871	
Sweden	800 / 6	Self regeneration, poorly drained, mean estimate	50	-460 to -37[c]			-460 to -37	-460 to -37	Lode, 2001
Finland	700 / 3.5	All: blocking ditches, additional water supply	10						Kivimäki *et al*., in press
		Pure stands of *E. vaginatum*, or *C. lasiocarpa*		-80[d]			-80	-80	
		Mixed stands of *E. vaginatum* and *C. lasiocarpa*		-320[d]			-320	-320	
		Bare plots		150[d,e]			150	150	
Finland	700 / 3.5	All: self regeneration, poorly drained	52						Yli-Petäys *et al*., 2007
		Wet: *S. pulcrum*		-143[d]	45		982	199	
		Dry: *S. papillosum, E. vaginatum, C. lasiocarpa*		40[d]	28		740	253	
Temperate									
the Netherlands	853 / 9	Damming of area	10	97	0	0	97	97	Nieveen *et al*., 1998
Ireland	804 / 9.3	All: blocking of ditches, flooding	10						Wilson *et al*., 2007
		Juncus, Holcus (drier places)		2281	0	0	2281	2281	
		Phalaris, Typha (wetter places)		1755	27.9	0	2453	1967	
		Eriophorum, Carex (wetter places)		1039	4.0	0	1140	1070	
		Bare soil		1019[e]	0	0	1019	1019	

Peatlands used for agriculture or forestry (see section 7.3)									
Boreal bogs									
Finland		Restored		-367[f]					Tolonen & Turunen, 1996
Sweden		natural		f	1,3 to 10,7	0,02	-329 to -94	-354 to -283	Nilsson et al., 2001; von Arnold et al., 2004
Sweden		Rewetted forest sites		-294	3	0,02	-213	-268	Nilsson & Nilsson, 2004
Boreal fens									
Finland		Restored		-55[f]					Tolonen & Turunen, 1996
Sweden		natural		f	4 to 22,7	0,03	54 to 521	-20 to 122	Nilsson *et al.*, 2001; von Arnold et al., 2004
Sweden		Rewetted forest sites		-110	27	0,03	574	100	Nilsson & Nilsson, 2004
Temperate bogs									
S Germany	1483 / 8.3	Drained and peat cutting (control 1)		1472	0,07	0,17	1525	1499	Drösler, 2005
		Drained (control 2)		864	1,9	0	911	878	
		Blocking ditches, damming	1-10	466	4,8	0	586	502	
		Natural		-264	25,9	0	383	-67	
Temperate fens									
the Netherlands	790 / 9.8	Non rewetted control		2545[g]	0	1.47	2983	2770	Jacobs *et al.*, 2003
		Raising water table	31	1915[g]	0	0.97	2204	2063	
NE Germany	544/8.1	Flooded (0.2 to 1 m)	1	-917	0	0.22	-851	-883	Augustin, unpublished
		Low intensity pasture, raising water table	16	-2383	267	0	4300	-352	
NW Germany	697/8.7	Non rewetted control, unfertilized		1511[e]	-0.1	0.79	1744	1631	Meyer *et al.*, 2001
		Rewetting by ditches	4-5	1584[e]	-0.1	1.01	1882	1737	
		Flooding (0.1 m)	1-2	1833[e]	101	-0.07	4329	2588	

[a] GWP after Forster *et al.*, 2007. For 100 year time horizon GWP is 25 and 298 g CO_2-e for CH_4 and N_2O, respectively. For 500 year time horizon GWP is 7.6 and 153 g CO_2-e for CH_4 and N_2O, respectively.

[b] CO_2 emission from straw included

[c] net long-term peat accumulation

[d] values measured for growing season (June-Sept) were corrected by respiration in winter 70 g CO_2 m^{-2} yr^{-1} (Alm *et al.*, 1999b).

[e] bare soil

[f] values for all three gases were combined from Finnish and Swedish studies to calculate GWP

[g] carbon exportation by harvesting was included

of CO_2, if compared to North European restored cutover bogs. One reason is the decomposition of mulch straw, used in restoration to favour the establishing of *Sphagnum* mosses. As this straw would also be decomposed following other uses (e. g. ploughing under or organic fertilization) and as it is a renewable C source at a short term, it needs not be considered in the GWP of the restored cutover bog. Furthermore, this case study was done three years after starting restoration, and it is known that successful restoration needs more time. There is a need for more studies on greenhouse gas emissions on restored North American peatlands.

Greenhouse gas emissions and GWP from restored temperate cutover peatlands seem to be much higher. Nevertheless, contradicting results are reported. Whereas Dutch cutover bogs show rather low GWP (97 g CO_2-e m^{-2} yr^{-1}) very high values are reported for Irish bogs, lying one order of magnitude higher than the Dutch or North European results. In temperate peatlands, peat mineralisation is favoured by mild winters, possibly enhanced by slightly increasing temperatures in the last decade due to climate change. Therefore the need for optimal conditions for the growth of peat forming plants in the summer months is much higher under temperate than under boreal conditions because higher winter C losses have to be compensated for. For restored temperate bogs in South Germany, under high precipitation rates, a GWP of 502 g CO_2-e m^{-2} yr^{-1} was determined on a 500 year basis. Thus, these restored bogs emit greenhouse gases into the atmosphere in contrast to natural bogs. After 1 to 10 years of restoration the optimal conditions for low greenhouse gas emissions had not been achieved at the restored site. Nevertheless the greenhouse gas emissions were already much lower than from non-restored peatlands (Drösler, 2005).

From restored temperate fens contradicting results are reported. In Northeast Germany flooding or raising the water table lead to CO_2 uptake of the peatland and the GWP, at least on a 500 year basis, was positive. In contrast, in Northwest Germany high CO_2 emissions were observed after rewetting by ditches or flooding. Eventhough this study was performed on bare soil and photosynthesis as a C sink process was excluded, it cannot be assumed that this process together with the root respiration will lead to a large accumulation of carbon in soil. Also, Wilson *et al*. (2007) (Figure 7.1) detected lower NEE for CO_2 from bare than from vegetated plots. Both German studies confirm that flooding leads to very high CH_4 emissions up to 267 g CH_4 m^{-2} $y4^{-1}$. Methane emission can be avoided, if a small oxic zone (10 cm) is maintained at peat surface where CH_4 oxidation will take place.

Nitrous oxide emissions from restored boreal bogs and fens were generally very low. The GWP of the determined emissions is about 0 to 5 g CO_2-e m^{-2} yr^{-1}. For restored temperate fens N_2O-based GWP up to 155 g CO_2-e m^{-2} yr^{-1} on a 500 years basis was measured.

Several factors conditioning or limiting the success of restoration measures and their impact on greenhouse gas emissions were not assessed in direct measurements. First of all there are technical limitations for optimal rewetting conditions. For example, due to loss in buoyancy, shrinkage and peat mineralization the peatland surface is not flat anymore and it becomes difficult to establish the optimal flooding level for peat growth together with low CH_4 emissions. The spatial distribution of greenhouse gas exchange between the peatland and the atmosphere needs further examination. Also, the availability of water for rewetting may be limited. In summer, the water loss by evaporation has to be compensated for, which is difficult if the hydraulic conductivity of the peat is reduced by degradation and especially if the peatland is grown on low permeable mud, impeding water supply from groundwater.

Secondly, political, social and global factors play an important role in restoration success and climate change mitigation by peatland restoration. For example, rewetting may need landscape planning involving different land owners. Compromises have to be made, permitting agricultural land-use in summer, e.g. at least temporary draw down of the water table. This may strongly limit the success of peatland restoration for climate change mitigation. In the summer months peat mineralisation is most intensive and water most limited. Moreove, the predicted temperature rise and mild winters will favour peat mineralisation and increase the emissions of greenhouse gases of peatlands on a long term basis.

Peatland restoration might be a very cost-efficient solution for greenhouse gas mitigation compared to technical solutions, e.g. insulation of buildings, renewable energy sources or wind energy (Joosten & Augustin, 2006). Nevertheless, a cost-efficiency analysis has to be done for each case individually. Costs should include one-off costs, e.g. restoration measures and land acquisition, and on the other hand running expenses, e.g. maintenance and annual interests or capitalization of investments. One-off costs of 400 € per ha in Ireland (restoration measures, Box 7.5) and 1 000 to 2 000 € per ha in Sweden (Lundin, personal communication) are reported. In Canada the costs of restoration including *Sphagnum* transfer, mulching and blocking the ditches also varies from 1 000 to 2 000 € per ha (Rochefort, personal communication). For the restoration of 10 000 ha of fens in Northeast Germany about 30 million € is planned to be spent between 2000 and 2008, corresponding to 3 000 € per ha, for land acquisition, water management, planting of trees, opening of dams and infrastructural measures, e.g. construction of bridges and lanes (LUNG, 2006). Assuming a long-term interest rate of 3 %, the annual costs due to capitalization interests amount to 12 - 90 € per ha. If a reduction in greenhouse gas emissions of about 1 000 g CO_2-e m^{-2} yr^{-1} is assumed (e.g. Box 7.5 or Box 7.7) the cost per tonne of CO_2-e mitigation is between 1.2 and 9 € per year. To date (appointed date: 05.03.2008) the EU Emission Allowances are listed at 0.03 € per tonne on the stock market CARBIX (Available http://www.eex.com) and are too low to cover the restoration costs. Nevertheless, the Second Period European Carbon Futures are listed at 21.15 € per t (2008) to 24.17 € per tonne (2012) at the derivatives market, indicating increasing prices in the forthcoming years. This will greatly improve the cost efficiency of peatland restoration projects if the greenhouse gas sequestration potential is included.

Of course, additional effects of peatland restoration should be considered as well. Peatland restoration is, in general, not necessarily designed for mitigation of greenhouse gas emissions. There are different objectives for peatland restoration, e.g. protection of rare species or biodiversity (birds, plants and animals), ecosystem restoration, or tourism. The different objectives necessitate different measures and different conditions. For example, it might be difficult to establish a water table equally favourable for waterfowl, breeding birds and *Sphagnum* growth. Nevertheless, it has to be kept in mind that peatland ecosystems are unique in their function as a sink for atmospheric CO_2. If rewetting is planned the re-establishing of this function should be of pre-eminent importance.

7.6. Literature cited

Alm, J., Saarnio, S., Nykänen, H., Silvola, J., Martikainen, P.J. 1999b. Winter CO_2, CH_4 and N_2O fluxes on some natural and drained boreal peatlands, *Biogeochemistry*, 44, 163-186.

Alm, J., Schulman, L., Walden, J., Nykänen, H., Martikainen, P.J., Silvola, J. 1999a. Carbon balance of a boreal bog during a year with exceptionally dry summer, *Ecology*, 80, 161-174.

Alm, J., Talanov, A. Saarnio, S., Silvola, J., Ikkonen, E., Aaltonen, H. Nykänen, H., Martikainen, P.J. 1997. Reconstruction of the carbon balance for micro sites in a boreal oligotrophic pine fen, Finland, *Oecologia*, 110, 423-431

Andersen, R., Francez, A.J., Rochefort L. 2006. The physicochemical and microbial status of a restored bog in Québec: identification of relevant criteria to monitor success, *Soil Biology and Biochemistry*, 38, 1375-1387.

Augustin, J., Joosten, H. 2007. Peatland rewetting and the greenhouse effect, *International Mire Conservation Group Newsletter*, 3, 29-30.

Beuving, J., van den Akker, J.J.H. 1996. *Maaiveldsdaling van veengrasland bij twee slootpeilen in de polder Zegvelderbroek*, Vijfentwintig jaar zakkingsmetingen [in Dutch], SC-DLO report 377, Wageningen, The Netherlands.

Blankenburg, J., Tonnis, W.E. 2004. *Guidelines for wetland restoration of peat cutting areas*, Bremen, Geological Survey of Lower Saxony, 56 pp.

Bortoluzzi, E., Epron, D., Siegenthaler, A., Gilbert, D., Buttler A. 2006. Carbon balance of a European mountain bog at contrasting stages of regeneration, *New Phytologist*, 172, 708-718.

CARBIX. 2008. Available: http://www.eex.com/en/Market%20Information/Emission%20Allowances/EU%20Emission%20Allowances%20%7C%20Spot and http://www.eex.com/en/Market%20Information/Emission%20Allowances/EU%20Carbon%20Futures%20%7C%20Derivatives

Cleary, J., Roulet, N.T., Moore, T.R. 2005. Greenhouse Gas Emissions from Canadian Peat Extraction, 1990-2000: A Life-cycle Analysis. Ambio, Vol. 34, No.6.

Cooper, D. J., Macdonald, L.H., Wenger, S.K., Woods, S.W. 1998. Hydrologic restoration of a fen in Rocky Mountain National Park, Colorado, USA, *Wetlands*, 18, 335-345.

Cooper, D.J., MacDonald, L.E. 2000. Restoring the vegetation of mined peatlands in the southern Rocky Mountains of Colorado, USA, *Restoration Ecology*, 8, 103-111.

Drösler, M. 2005. *Trace gas exchange and climatic relevance of bog ecosystems, Southern Germany*, Ph.D. thesis, Technical University of Munich, Germany. 179 pp.

Ferland, C., Rochefort, L. 1997. Restoration techniques for *Sphagnum*-dominated peatlands, *Canadian Journal of Botany*, 75, 1110-1118

Forster, P., V. Ramaswamy, P. Artaxo, T. Berntsen, R. Betts, D.W. Fahey, J. Haywood, J. Lean, D.C. Lowe, G. Myhre, J. Nganga, R. Prinn, G. Raga, M. Schulz and R. Van Dorland, (2007): Changes in Atmospheric Constituents and in Radiative Forcing. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Girard, M., Lavoie, C., Thériault, M. 2002. The regeneration of a highly disturbed ecosystem: a mined peatland in southern Québec, *Ecosystems*, 5, 274-288.

Gorham, E. 1991. Northern peatlands: role in the carbon cycle and probable responses to climatic warming, *Ecological Applications*, 1, 182-195.

Gorham, E., Rochefort, L. 2003. Peatland restoration: A brief assessment with special reference to *Sphagnum* bogs, *Wetlands Ecology and Management*, 11, 109-119.

Groeneveld, E.V.G., Massé, A., Rochefort, L. 2007. *Polytrichum strictum* as a nurse-plant in peatland restoration, *Restoration Ecology*, 15, 709-719.

Jacobs, C.M.J., Moors, E.J., van der Bolt, F.J.E. 2003. *Influence of water management on coupled greenhouse gas emissions in the peat meadow area close to R.O.C. Zegveld* [in Dutch], Alterra report 840, Wageningen, The Netherlands.

Joosten, H., Augustin, J. 2006. Peatland restoration and climate: On possible fluxes of gases and money, In *Proceedings of the International conference Peat in solution of energy, agriculture and ecology problems*, Minsk (Weisrussland) 2006, pp. 412-417.

Kasimir-Klemedtsson, Å., Klemedtsson, L., Berglund, K., Martikainen, P., Silvola, J., Oenema, O. 1997. Greenhouse gas emissions from farmed organic soils: a review, *Soil Use and Management*, 13, 245-250.

Kivimäki, S., Yli-Petäys, M., Tuittila, E.-S. in press. Carbon sink function of sedge and Sphagnum patches in a restored cut-away peatland: increased functional diversity leads to higher production, *Journal of Applied Ecology*.

LUNG (Landesamt für Umwelt, Naturschutz und Geologie Mecklenburg-Vorpommern). 2006. *Richtlinie zur Förderung von Maßnahmen zum Schutz und der Entwicklung von Mooren in Mecklenburg-Vorpommern, Sachstandsbericht zur Umsetzung, Koordinierungsstelle Moorschutz*.

Langeveld, C.A., Segers, R., Dirks, B.O.M., Van den Pol-van Dasselaar, A., Velthof, G.L., Hensen, A. 1997. Emissions of CO_2, CH_4 and N_2O from pasture on drained peat soils in the Netherlands, *European Journal of Agronomy*, 7, 35-42.

Lode, E. 2001. *Natural Mire Hydrology in Restoration of Peatland Functions*, Ph.D. Thesis, Acta Universitatis Agriculturae Sueciae, Silvestria 234, SLU, Uppsala, Sweden.

McNeil, P., Waddington, J.M. 2003. Moisture controls on Sphagnum growth and CO_2 exchange on a cutover bog, *Journal of Applied Ecology*, 40, 354-367.

Meyer, K., Höper, H., Blankenburg, J. 2001. Spurengashaushalt und Klimabilanz von Niedermooren unter dem Einfluß des Vernässungsmanagements, In *Ökosystemmanagement für Niedermoore, Strategien und Verfahren zur Renaturierung*, Kratz, R. & Pfadenhauer, J. (eds.), Ulmer, Stuttgart, pp. 104-111.

Nieveen, J.P., Jacobs, C.M.J., Jacobs, A.F.G. 1998. Diurnal and seasonal variation of carbon dioxide exchange from a former true raised bog, *Global Change Biology*, 4, 823-833.

Nilsson, K., Nilsson, M. 2004. *The climate impacts of energy peat utilisation in Sweden the effect of former land-use and after-treatment*, IVL Swedish Environmental Research Institute, Report B1606, Stockholm, 92 pp.

Nilsson, M., Mikkelä, C., Sundh, I., Granberg, G., Svensson, B.H., Ranneby, B. 2001. Methane emissions from Swedish mires: National and regional budgets and dependency on mire vegetation, *Journal of Geophysical Research*, 18, 20,487-20,860.

NLWKN (Niedersächsischer Landesbetrieb für Wasserwirtschaft, Küsten- und Naturschutz). 2006. *25 Jahre Niedersächsisches Moorschutzprogramm - eine Bilanz*, Informationsdienst Naturschutz Niedersachsen 3/2006, NLWKN, Hannover, Germany, pp. 154-180

NLWKN (Niedersächsischer Landesbetrieb für Wasserwirtschaft, Küsten- und Naturschutz). 2007. *LIFE-Natur Projekte zur Wiedervernässung der Dümmerniederung*, NLWKN, Oldenburg, Germany, 11 pp.

Petrone, R.M., Waddington, J.M. 2001. Ecosystem scale evaporation and net CO_2 exchange from a restored peatland, *Hydrological Processes*, 15, 2839-2845.

Poulin, M., Rochefort, L., Quinty, F., Lavoie, L. 2005. Spontaneous revegetation of mined peatlands in eastern Canada, *Canadian Journal of Botany*, 83, 539–557.

Quinty, F., Rochefort, L. 2003. *Peatland restoration guide: 2nd edition*, Canadian Sphagnum Peat Moss Association, New Brunswick Department of Natural Resources and Energy, Québec City, Canada.

Rowlands, R.G. 2001. *The ecological restoration through natural revegetation of industrial cutaway peatlands in Ireland*, Ph.D. Thesis, Department of Environmental Resource Management, University College Dublin, 243 pp.

Schouwenaars, J.M. 1988. The impact of water management upon groundwater fluctuations in a disturbed bog relict, *Agricultural Water Management*, 14, 439–449.

Schouwenaars, J.M. 1993. Hydrological differences between bogs and bog-relicts and consequences for bog restoration, *Hydrobiologia*, 265, 217-224.

Tolonen, K., Turunen, J. 1996. Accumulation of carbon in mires of Finland and implications for climate change, *The Holocene*, 6, 171-178.

Tuittila, E.-S., Komulainen, V-M., Vasander, H., Laine, J. 1999. Restored cut-away peatland as a sink for atmosperic CO_2, *Oecologia*, 120, 563-574.

van den Pol-van Dasselaar, A., van Beusichem, M.L., Oenema, O. 1999. Determinants of spatial variability of methane emissions from wet grassland on peat soil, *Biogeochemistry*, 44, 221-237.

Vasander, H., Tuittila, E-S., Lode, E., Lundin, L., Ilomets, M., Sallantaus, T., Heikkilä, M-L., Laine, J. 2003. Status and restoration of peatlands in nothern Europe, *Wetlands Ecology and Management*, 11, 51-63.

von Arnold, K. 2004. *Forests and greenhouse gases. Fluxes of CO_2, CH_4 and N_2O from drained forests on organic soils*, Linköping Studies in Arts and Science No 302, Linköping University, Sweden.

Waddington, J.M., Day, S.M. 2007. Methane emissions from a cutover peatland following restoration, Journal of Geophysical Research, 112, G03018, doi: 10.1029/2007JG000400.

Waddington, J.M., Greenwood, M.J., Petrone, R.M., Price, J.S. 2003. Mulch decomposition impedes net recovery of carbon sink, *Ecological Engineering*, 20, 199-210.

Waddington, J.M., Price, J.S. 2000. Effect of peatland drainage, harvesting, and restoration on atmospheric water and carbon exchange, *Physical Geography*, 21, 433-451.

Waddington, J.M., Toth, K., Bourbonniere, R.A. 2007. Dissolved organic carbon export from a cutover and restored peatland, *Hydrological Processes*, [published online], doi: 10.1002/hyp.6818.

Waddington, J.M., Warner, K.D. 2001. Atmospheric CO_2 sequestration in restored mined peatlands, *Ecoscience*, 8, 359-368

Waddington, J.M., Warner, K.D., Kennedy, G.W. 2002. Cutover peatlands: A consistent source of CO_2, Global Biogeochemical Cycles, 16, 1002, doi: 10.1029/2001GB001398.

Wilson, D., Tuittila, E.-S., Alm, J., Laine, J., Farrell, E.P., Byrne, K.A. 2007. Carbon dioxide dynamics of a restored maritime peatland, *Ecoscience*, 14, 71-80.

Yli-Petäys, M., Laine, J., Vasander, H., Tuittila, E.-S. 2007. Carbon gas exchange of a re-vegetated cut-away peatland five decades after abandonment, *Boreal Environment Research,* 12, 177-190.