Chapter 1

General introduction

1.1 Human influence on global climate

Climate change

An important indicator of global climate change is the mean global surface temperature. This temperature has increased since 1861 and is rapidly rising since 1980 (Figure 1). Changes have also occurred in other important aspects of climate, especially changes in the frequency and intensity of precipitation (IPCC, 2001). The Intergovernmental Panel on Climate Change (IPCC) concluded in its Second Assessment Report ‘Climate Change 1995’ that the increase in mean global surface temperature is “unlikely to be entirely due to natural fluctuations of the climate system”. It furthermore states that, while it remains difficult to quantify the climate impacts of human activity, global climate “is expected to continue to change in the future” (IPCC, 1995).

Acknowledging that many factors currently limit our ability to project and detect future climate change, the IPCC calls for further scientific work on a number of priority topics in order to reduce the uncertainties and the policy-related problems. One of these topics is estimating future emissions and biogeochemical cycling of greenhouse gases (GHG), including assessment of temporal and regional variability (IPCC, 1995; IPCC, 2001).

Figure 1. Annual anomalies of global average land-surface air temperature (°C), 1861 to 2000, relative to the average for 1961–1990 (IPCC, 2001).
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The greenhouse effect and global warming

The natural greenhouse effect is the property of Earth’s atmosphere to absorb some of the thermal (long-wave) radiation that is emitted by the surface that is heated by solar (short-wave) radiation (Figure 2). This trapping of thermal radiation, which keeps the Earth’s annual global surface and troposphere temperature at about +15°C, is caused by clouds and by naturally occurring atmospheric GHG, principally water vapor (H2O), but also carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O) and ozone (O3).

Without the natural greenhouse effect, the average global temperature would be about −18°C. Increasing GHG concentrations in the atmosphere, if not neutralized by other effects, will cause an additional warming of the atmosphere and of the Earth surface. The observed increase in the mean global surface temperature is thought to have resulted at least in part from man-induced increasing GHG concentrations (see below). In this respect reference is often made to (1) the (enhanced) greenhouse effect, (2) global warming, or (3) a positive radiative forcing (Figure 3). Radiative forcing is also influenced by processes like solar variability and volcanic activity (IPCC, 2001).

The relative contribution to global warming by atmospheric emission of a particular GHG is usually compared to that of CO2 by using the Global Warming Potential (GWP) index, taking into account the atmospheric lifetimes of the different gases. For instance, the GWP of CH4 for a time horizon of 100 years is 23, which means that 1 kg of atmospheric CH4 is 23 times as effective in absorbing radiation as 1 kg of atmospheric CO2 (IPCC, 2001).

Increasing concentrations of greenhouse gases

Since the beginning of the industrial revolution (about 1750 AD) the atmospheric concentrations of important GHG have grown significantly: CO2 increased from about 280 ppmv to almost 367 ppmv (31%), CH4 rose from 700 ppbv to 1745 ppbv (150%), and N2O from about 268 ppbv to 314 ppbv (17%) (Figure 3) (IPCC, 2001). This trend can be attributed largely to human activities, mostly burning of fossil fuel, land-use change and agriculture (Table 1). Concentrations of other anthropogenic GHG, like chlorofluorocarbons (CFCs) and tropospheric ozone (O3), have also increased. It is assumed
that the observed increase in mean global temperature is related, at least to some extent, to this large and increasing growth in anthropogenic GHG emissions (IPCC, 2001).

Figure 3. Changes in the atmospheric concentrations of carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) over the past 1000 years. The estimated positive radiative forcing of the climate system from these gases is indicated on the second y-axis (IPCC, 2001).


<table>
<thead>
<tr>
<th>Source/Process</th>
<th>CH₄ (Mt yr⁻¹)</th>
<th>CO₂ (Gt yr⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>anthropogenic sources</strong></td>
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<tr>
<td>energy related</td>
<td>range¹</td>
<td>fossil fuel burning and cement production</td>
</tr>
<tr>
<td>landfills</td>
<td>75–110</td>
<td>19.8 ± 1.1</td>
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<tr>
<td>ruminants (enteric fermentation)</td>
<td>35–73</td>
<td>land use change (incl. drainage peatlands)</td>
</tr>
<tr>
<td>waste treatment</td>
<td>80–115</td>
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<tr>
<td>rice agriculture</td>
<td>14–25</td>
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<tr>
<td>biomass burning</td>
<td>25–100</td>
<td></td>
</tr>
<tr>
<td>other</td>
<td>80–115</td>
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<td>oceans</td>
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<tr>
<td>other</td>
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</tr>
<tr>
<td><strong>total sources</strong></td>
<td>500–600²</td>
<td>26.0</td>
</tr>
<tr>
<td><strong>sinks</strong></td>
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<tr>
<td>soils</td>
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<td>ocean uptake</td>
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<td>terrestrial uptake</td>
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<td>7.0 ± 4.8</td>
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<tr>
<td><strong>total sinks</strong></td>
<td>460–580²</td>
<td>13.9</td>
</tr>
<tr>
<td><strong>atmospheric increase</strong></td>
<td>20–52²</td>
<td>12.1 ± 0.4</td>
</tr>
</tbody>
</table>

¹ Different sources; adapted from IPCC’s Third Assessment Report (TAR) (IPCC, 2001).
² Values used in TAR; (sources 598) – (sinks 576) = atmospheric increase 22).
³ Values used in TAR.
⁴ An atmospheric increase of 1 Gt Carbon corresponds with 0.47 ppmv.
Chapter 1

1.2 Peatlands in the temperate zone\(^1\) and their role in biogeochemical cycling

Peatlands: sink or source?

Northern (boreal and subarctic) peatlands occupy only about 2.5% (346–371 x 10\(^6\) ha) of the global terrestrial surface, but contain approximately 32% of the total organic C of the world’s soils (Armentano and Menges, 1986; Gorham, 1991). The estimated amount (about 455 Gt) of carbon accumulated in these peatlands during the last 10,000 years equals 40–60% of the present atmospheric carbon pool (Gorham, 1991). Peatlands have been a net sink of carbon for many centuries, but evidence is accumulating that the uptake of carbon in peatlands is now exceeded by carbon release (both as CO\(_2\) and CH\(_4\)). Armentano and Verhoeven (1990), for example, calculated a net release from peatlands of about 24 Mt carbon yr\(^{-1}\). This shift in balance is mainly the result of changes in drainage and land use, and indicates that peatlands are changing from net sinks into net sources in the global carbon and GHG cycles. In turn, climate change may also alter the carbon dynamics of peatlands. Increased decomposition rates through warmer conditions and reduced soil moisture content may lead to large carbon losses to the atmosphere, particularly from northern peatlands. Higher temperatures may also lead to enhanced CH\(_4\) emissions from subarctic wetlands as a result of reduction of permafrost. Changes in regional hydrology, caused by precipitation changes, may lead to loss or new growth of wetlands locally (IPCC, 2000).

Drainage effects on the emission of greenhouse gases

Peat soils in northern latitudes are commonly drained for cultivation. According to Gorham (1991) and Armentano and Menges (1986) 12-20 x 10\(^6\) ha of the peatlands from an original area of about 346 x 10\(^6\) ha are drained. An increase in the rate of mineralization of organic matter can be expected as a result of more oxygenated conditions and further soil management (ploughing, fertilization) (Nykänen et al., 1995). Natural Finnish peatlands, for example, accumulate 81-230 kg CO\(_2\)-C per hectare annually (Vasander, 1996). When drained for agriculture, these peatlands may revert from CO\(_2\) sink to source (Armentano and Menges, 1986; Martikainen et al., 1995; Nykänen, et al., 1995). On the other hand, a drawdown of the water table in peatlands reduces CH\(_4\) emission due to decreased production and increased CH\(_4\) oxidation (Moore and Knowles, 1989; Roulet et al., 1992). When drained, peatlands can even act as a sink for atmospheric CH\(_4\) (Freeman et al., 1993; Martikainen, et al., 1995; Moore and Knowles, 1989). At present, however, wetlands (including peatlands) are still the world’s largest natural source of atmospheric CH\(_4\) (Table 1).

Peatlands in the Netherlands

Most studies on GHG emission from (drained) peatlands generally pertain to (boreal) continental peatlands (Goosen et al., 1996). Emissions from coastal peatlands\(^2\), which comprise considerable volumes of peat (Godwin, 1978; Van de Plassche et al., 1987), have received much less attention.

At present, approximately 294.000 ha or 9.5 % of the Netherlands consist of peatland, defined as soil with more than 50% of organic material in the upper 80 cm (SC-DLO, 1992). If the category of peaty (so-called “moerige”) soils (>15–30 % of organic matter in the upper 40 cm) is included, the total peat area in the Netherlands amounts to about 450.000 ha (Hendriks, 1991). About 160.000 ha of these peatlands are found in the

\(^1\) Since the research project concerns the western Netherlands, emphasis is placed on peatlands in the temperate zone

\(^2\) For the purpose of this study, coastal peatlands are defined as coastal plain areas underlain by peat deposits (locally intercalated with clastic deposits), genetically related to coastal depositional environments such as marshes, lagoons, deltas and coastal river plains
western part of the Netherlands (80% peat and 20% peaty) (Figure 4). Over 90% of these peatlands are used for agricultural purposes.

Extensive and thick (up to 8 m) coastal peat deposits of Holocene age occur in the western Netherlands (Figure 4) as a result of continuous relative sea-level rise, gradual closure of the coastline since 6000 BP, and freshening of the intracoastal area by river discharge and groundwater seepage. Under conditions of a gradually decreasing rate of sea-level rise, and hence groundwater-level rise, large areas subsequently developed from fens into raised bogs. The first systematic, large-scale reclamation and cultivation of these coastal fenlands and bogs, which took place from the 10th to the 14th century, involved lowering of groundwater tables that initiated the processes of accelerated peat decomposition and lowering of the peat surface. Apart from decomposition, the process of peat subsidence can be attributed to several other processes, which include shrinkage and compaction of the peat as the water content is reduced, and aeolian and fluvial erosion of the peat surface. Assessments of the relative importance of these processes are, however, uncommon. By the middle of the 15th century, the surface of many peat areas in the western Netherlands had been lowered to the extent that the creation of (artificially drained) polders became necessary, thus continuing the cycle of drainage, compaction and oxidation of peat, surface lowering, and the subsequent need for further lowering of the water table (Van der Linden, 1982).

Over the past several hundred years, large-scale digging and dredging of peat (for fuel) and intensified drainage of agricultural peatlands caused accelerated peat oxidation and emission of CO₂. Reconstruction of the original peat topography is difficult due to insufficient data; Borger, 1992 calculated that in Roman times raised bogs reached as high as 2 m above present mean sea level, whereas wetlands along creeks reached 0.6 m above that level.

A rough estimate of the amount of peat that has disappeared since the 10th century, is obtained as follows. Today, the average elevation of coastal peatlands of the western Netherlands is about 2 m below current mean sea level. Assuming that the former peat surface reached to current mean sea level (bog peat above sea level is ignored), we arrive at a volume of coastal peat of at least 3.2*10⁹ m³ (160.000 ha * 2 m) which has disappeared as the result of man’s intervention. Compaction of the peat left aside, this amount of wasted peat is equivalent to about 0.2 Gt CO₂-C or an increase in global atmospheric CO₂ of 0.1 ppmv (calculated for a wet peat carbon content of 58 kg C m⁻³ (Gorham, 1991) and 1 Gt C is 0.47 ppmv). For comparison, present-day (1990–2000) total annual GHG emission in the Netherlands is about 225 Mt CO₂ equivalents (CBS and RIVM, 2001), which corresponds to an increase in global atmospheric CO₂ of 0.03 ppmv.

However, the amount of disappeared peat is likely to be a factor 1.2–1.5 larger than calculated. Other aspects than the ones already mentioned (i.e. the exclusion of bogs and compaction) are the area and thickness of the peat used in the calculation. The soil in many “droogmakerijen” (reclaimed lakes), like Beemster, Haarlemmermeer, etc., is no longer classified as peat soil due to large-scale digging and dredging of peat in the past (Verhoeven, 1992). This means that the former peat area was >160.000 ha. Furthermore, records show that in certain areas 5–6 m of the original peat layer has disappeared (Verhoeven, 1992), i.e. much more than the 2 m used in the estimate.

1 Other components in the carbon balance (e.g. uptake by the vegetation) are not included in this estimate.
Figure 4. Current distribution of peat soils in the western Netherlands (SC-DLO, 1992); according to the Dutch soil classification system, soil is classified as peat when between 0–80 cm depth more than half is organic (peaty) material; in the western Netherlands most peat is fen peat, or bog peat that has subsided and is nowadays influenced by surface- or groundwater.

Peat degradation in the western Netherlands continues today, as drainage continues, but the rate of degradation is not well known. To estimate the contribution of peat degradation in the western Netherlands to the annual GHG emission in the Netherlands, it is necessary to quantify the present-day CO₂ and CH₄ fluxes from these extensive peatland areas.

In recent years, government and private organizations concerned with nature management of coastal lowland areas in the Netherlands have advanced plans to convert agricultural land back into wetland-nature areas (LNV, 2000; VROM, 2000; VROM, 2001). Although ecological improvement and storage of water are the main objectives, policy makers also want to know whether carbon fixation in peat soils is an effective means to reduce GHG emissions. The assumption made by these policy makers is that higher water tables will enhance fixation of carbon by peat forming vegetation and reduce peat oxidation and CO₂ emission. However, higher water tables in peat soils will also enhance the production of CH₄, which is about 23 times as effective a GHG than CO₂ (IPCC, 2001). The net effect of elevating the water tables in former agricultural areas on the carbon- and GHG balances thus remains to be quantified.

To predict the net effect of (future) water-management operations on the GHG flux, we first need to know the present CO₂ and CH₄ fluxes from coastal peatlands in the western Netherlands and how these fluxes are influenced by environmental conditions and degradation processes.

Previous research on GHG fluxes from peatlands in the Netherlands

Previous (i.e. pre-1996) work on GHG emission from (peat) soils in the Netherlands was performed mainly since the early nineties. Most of these studies were carried out within the framework of the Dutch National Research Programme on Global Air Pollution and Climate Change (NOP). Within this programme, which started in 1989, Hensen et al. (1995) made aerodynamic CO₂ flux measurements from grassland on clay-on-peat soils (Cabauw) and found a net emission of 0.05–1.2 kg CO₂ m⁻² yr⁻¹ for the period 1993–1995. Hensen et al. (1995) also did eddy correlation CO₂ flux measurements from grassland on peat (Zegveld), but could not produce annual estimates since measurements were performed only from March to October 1993. In that period net CO₂ uptake occurred, but it was argued that on an annual basis the Zegveld site would also be a net source, albeit smaller than at the Cabauw site. Even though the measurements at Cabauw and Zegveld showed clear differences in CO₂ emission, Hensen et al. (1995) extrapolated the emission value for the Cabauw site to the total area of peat soils in the Netherlands (450,000 ha).
They calculated that the emission by these soils (0–5.4 Mt CO₂ yr⁻¹) was 0–3 % of the annual CO₂ emission from fossil fuels in the Netherlands (or 0–1.9 Mt CO₂ yr⁻¹ for the peatlands in the western Netherlands only). They concluded that the annual CO₂ emission from grassland on peat soil was most likely larger than the CO₂ uptake (through plant photosynthesis) because of the large component of soil respiration (caused by oxidation of organic carbon from both the peat and from applied organic manure).

Hensen et al. (1995) found that a high water-table site (30 cm below surface) and a low water-table site (60 cm below surface) in Zegveld did not yield significant differences in CO₂ fluxes. Night-time CO₂ emission (both plant- and soil respiration) showed a positive correlation with temperature (seasonal) and ranged from 0 to about 800 mg CO₂ m⁻² hr⁻¹ at Zegveld, and up to about 1500 mg CO₂ m⁻² hr⁻¹ at Cabauw.

Hendriks (1991) carried out a literature study of degradation and mineralization of peat in the Netherlands. This study focused mainly on phosphorus and nitrogen and had a clear agricultural scope, but dealt also with modelling and CO₂ release.

Van den Born et al. (1991) made a first estimate of the annual CH₄ emission from peat soils in the western Netherlands. By using published flux data (from areas with more or less similar conditions as in the Netherlands) and by subdividing the peat soils into five groundwater classes, they arrived at an annual CH₄ emission of 0.8–2.0 Mt CO₂-equivalents yr⁻¹ for a total area of 158,000 ha of peat soils in the western Netherlands. This amount equals 3–9 % of the estimated total annual CH₄ emission (960 kton CH₄ yr⁻¹) in the Netherlands (1989/1990).

Kengen and Stams (1995) performed incubation experiments with soil samples from two study areas in the western Netherlands (Zegveld, a drained, intensively managed grassland on peat soil; and Nieuwkoop, a non-drained, nature-reserve area with peat mosses on peat) and showed clear differences in CO₂ and CH₄ production with depth. The largest CO₂ and CH₄ production was measured in soil samples from the top layer (0–10 cm); this production decreased rapidly with depth. CO₂ production was almost zero below 60 cm. In soil samples from Zegveld, CH₄ production decreased markedly below 10 cm and was almost zero below 30 cm, likely due to the absence of easily degradable organic matter (Kengen and Stams, 1995). Similar results were observed for soil samples from the high and low water-table sites in Zegveld. CH₄ production in the soil samples from Nieuwkoop was larger, but decreased also with depth.

In the same study areas as used by Kengen and Stams (1995), Van den Pol-Van Dasselaar and Oenema (in Oenema, 1995) measured CH₄ fluxes in the field using closed chambers. CH₄ emission in Zegveld was small (<1 mg CH₄ m⁻² d⁻¹), and net uptake (<1 mg CH₄ m⁻² d⁻¹) occurred during the summer: CH₄ uptake was slightly larger at the low water-table site, compared to the high water-table site. CH₄ emission at Nieuwkoop, on the other hand, reached values of up to 215 mg CH₄ m⁻² d⁻¹ and showed large differences between different plots, indicating a strong influence of soil temperature and water-table depth (between 0 and 40 cm below surface).

In summary, previous research has dealt with various aspects of degradation processes in peat soils and several attempts have been made to quantify annual GHG emission from the peat soils in the western Netherlands. The reliability of these estimates is, however, subject to improvement. Previous work on peat soils in the western Netherlands was mostly semi-quantitative and aimed at gaining insight in the processes and factors influencing degradation processes, rather than at quantifying present-day or future GHG emission from larger areas. Most incubation studies, for example, used homogenized slurries for studying processes of peat decomposition. The use of intact peat cores (with living plants) is likely to yield more reliable and representative values for GHG emission, which will result in a more reliable upscaling. In conclusion, to obtain more reliable values of current and future GHG emission from the peat soils in the western Netherlands, a more comprehensive and coherent methodology is necessary. Fluxes of CO₂ and CH₄ should be measured simultaneously, both in incubation and in field experiments. Results from these experiments can be used to develop a process-based simulation model that includes also peat as a pool of organic matter. By developing such a model, which is not yet available, in tandem with the measurements both approaches can benefit from each other.
1.3 The research project “Human influence on carbon fluxes in coastal peatlands”

Objective

The aim of this study is to develop a methodology, including a simulation model, for improved quantification and prediction of carbon fluxes in coastal peatlands subject to land and water management. Specifically, the objectives are to develop a numerical model and quantify (1) present-day CO2 and CH4 fluxes from the extensive peatland areas in the western Netherlands, and (2) future GHG fluxes for different climate, water-management and land-use scenarios. Because peatlands in the western Netherlands are no longer actively growing, it is assumed that the carbon uptake by primary production of the vegetation is balanced by the carbon release from respiration and consumption (grazing or harvest). This study therefore focuses mainly on CO2 and CH4 fluxes related to degradation processes in peat soils, whereas carbon fluxes concerning living vegetation are, initially, left aside.

Approach and methods

A literature study was made of the different biogeochemical processes operating in coastal peat soils and the dominant factors influencing the carbon cycle. Within a complicated network of interactions, the most important factors on the mineralization of peat were found, or presumed, to be water-table depth, temperature, peat thickness and composition, water quality, fertilization, and history in land use.

Incubation experiments with intact peat columns were carried out in the laboratory, with the objective to determine the effect of changes/differences in temperature, water-table depth, peat thickness, and peat composition on the CH4, CO2, and O2 fluxes. The results from this study are presented in chapter 2 and used in the modelling process (chapter 4).

To assess the present-day contribution of peat degradation in (cultivated) coastal peatlands to the annual emission of GHG in the Netherlands, gas fluxes were measured (from November 1998 until August 2000) at three selected study areas in the western Netherlands (Ransdorp, Guisveld and Kamerik). The objective of this field study, the results of which are presented in chapter 3, was to quantify the influence of various in situ environmental conditions on the CO2 and CH4 fluxes from peat soils, and to provide flux data over a wide range of these environmental conditions for validation of the process-based simulation model. The three study areas, all grassland on peat soil, are representative of different peat soils found in the western Netherlands. Guisveld is a wetland-nature area, with high groundwater levels (i.e. up to a few cm below the surface). The soil in Ransdorp is very similar to Guisveld, but has a strongly humic surface layer (0–30 cm) of crumbly sandy clay; the area is intensively managed (drainage and application of manure). The study area Kamerik is extensively managed and is characterized by the presence of thick (max. 6 m) layers of eutrophic (wood and sedge) peat with a topsoil (0–30 cm) of anthropogenic origin.

Closed chambers, in combination with a portable infra-red gas analyzer (IRGA) and gas chromatography, were used to enable the measurement of within-area and between-area differences in CO2 and CH4 fluxes. In contrast, the Eddy-correlation method, which uses a meteorological tower with several gas sensors, measures gas fluxes over a larger area. It was not possible to include such measurements in this study due to financial limitations. To obtain representative average fluxes per study area and to investigate within-area variation, five measurement sites per study area were used.

Based on the analysis of several existing models and by using the results from the incubation and field experiments, a new process-based model (“PEATLAND”) was developed for simulation of peat degradation in coastal peatlands and for quantifying CO2 and CH4 fluxes. This is the first model that includes the peat substrate itself as an organic matter pool and in which CO2 and CH4 are closely linked. Details of the model and the modeling process are described in chapter 4. An assessment is made of CO2 and CH4 fluxes for different climate and management scenarios in coastal peatlands in the western Netherlands.
Netherlands by applying the model to regional data on soil and hydrology in a GIS environment (chapter 5).

Results from the wetland-nature area Guisveld indicate a strong influence of high water tables on the CO₂ and CH₄ fluxes, but in situ investigation of the effect of elevating water tables in agricultural peatland areas was not possible in this study. Policy makers wish to know whether carbon fixation in peat soils effectively reduces GHG emissions when agricultural peatlands are (for purposes of nature development) converted back into wetland-nature areas. Chapter 6 therefore evaluates published rates of CO₂ fixation and CH₄ release in natural (non-drained) peatlands. It turns out that under wet circumstances the large CH₄ emission, expressed in CO₂-equivalents, is likely to balance or even exceed the increased CO₂ uptake by the vegetation. For the western Netherlands, however, a significant net reduction of GHG emission will occur, due to the large decrease in present CO₂ emission caused by peat degradation (oxidation).

The final chapter (#7) discusses present-day and future CO₂ and CH₄ fluxes.

1.4 References


1.5 Appendix

Units and conversions

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<tbody>
<tr>
<td>ha</td>
<td>Hectare</td>
<td>10 000 m²</td>
</tr>
<tr>
<td>ppmv</td>
<td>Parts per million ((10^6)) by volume</td>
<td></td>
</tr>
<tr>
<td>ppbv</td>
<td>Parts per billion ((10^9)) by volume</td>
<td></td>
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<tr>
<td>Gt</td>
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<td>(10^{15}) g</td>
</tr>
<tr>
<td>Mt</td>
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<td>(10^{12}) g</td>
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\[ \text{Carbon mass CO}_2 = \frac{3}{11} \times \text{mass CO}_2 \]
\[ \text{Carbon mass CH}_4 = \frac{3}{4} \times \text{mass CH}_4 \]

\[ \text{mm (peat) accumulation} \times 0.58 = \text{t CO}_2 - \text{C ha}^{-1} \text{yr}^{-1} \]