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The Climate Impact of Energy Peat Utilisation in Sweden – the Effect of former Land-Use and After-treatment

Kristina Nilsson, Mats Nilsson

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Organisation/Organization
IVL Svenska Miljöinstitutet AB
IVL Swedish Environmental Research Institute Ltd.

Adress/address
Box 210 60
100 31 Stockholm

Telefonnr/Telephone
08-598 563 10

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Kristina Nilsson IVL, Swedish Environmental Research Institute
Mats Nilsson, Department of Forest Ecology, Swedish University of Agricultural Sciences

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The Climate Impact of Energy Peat Utilisation in Sweden – the Effect of former Land-Use and Aftertreatment

Sammanfattning/Summary
The potential climate impact (radiative forcing) from peat extraction at different types of peatlands (with different land-use history) has been investigated. The climate impact considered emissions/uptake of carbon dioxide, methane and nitrous oxide before, during and after the peat extraction and combustion The four types investigated were:
1. Pristine mires
2. Organic agricultural soils
3. Drained forests and
4. Abandoned harvesting area subjected to previous peat extraction.
Two types of after-treatments were used in the scenarios: rewetting or afforestation.
The climate impact of the use of energy peat in Sweden was estimated based on description of mire type and former land-use of the peat-harvesting areas. The result show that the climate impact of current Swedish use of energy peat will give a smaller climate impact than the use of coal but a larger impact than the use of natural gas. It also shows that there is a potential of reducing the climate impact from peat utilisation by choosing extraction area and aftertreatment methodology.

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Abstract

The potential climate impact from the use of peat for energy production in Sweden was evaluated in terms of contribution to atmospheric radiative forcing. The calculations consider emissions from combustion and from the peatlands before, during and after harvesting. Four main groups of peatlands in use for peat harvesting were identified:

1. pristine peatlands
2. drained peatlands used for agriculture
3. drained peatlands used for forestry (low productive)
4. peatlands previously (historically) used for peat harvesting

The radiative forcing of different scenarios using the mentioned peatland types for energy peat production was calculated, using literature and empirical data related to peat harvesting, at these four types of mires. In the calculations the original land-use was set as reference scenario. The radiative forcing caused by using agricultural peatlands for energy peat production was much lower than for the corresponding use of pristine peatlands and old peat harvesting areas. The calculated value for the radiative forcing of current (20-year period of harvesting and combustion) peat utilisation for energy in a 100-year perspective ranges between 80-90% of the corresponding radiative forcing from using coal and 165-180% from using natural gas. The scenarios for different peatland types and the currently used peatlands show that there is a potential to reduce the radiative forcing caused by energy peat production and utilisation in Sweden by selecting peat harvesting area and after-treatment method. It was concluded that both the greenhouse gas balance of the peatland before harvesting and the aftertreatment methods strongly impact the radiative forcing from energy peat utilisation.

The radiative forcing from continuous utilisation of energy peat was also calculated a few scenarios. The results show a slower development than the shorter harvesting/combustion scenarios. Since new peat continuously is burnt it will take longer time before the benefit of the avoided methane emissions at the initial mire and the larger uptake of carbon dioxide at the after-treated area will make an impact.

Sammanfattning

Syftet med denna studie var att uppskatta klimatpåverkan från dagens användning av energitorv i Sverige samt undersöka potentialen att minska denna genom val av täktområde och efterbehandlingsmetod. Klimatpåverkan avsågs omfatta emissioner av CO_2, CH_4 samt N_2O och inkluderade emissioner och upptag både före under och efter förbränning och brytning. Fyra typer av torvmarker (med olika markanvändning) identifierades och undersöktes med avseende på klimatpåverkan vid utvinning av energitorv. Dessa fyra torvmarkstyper är:

1. Orörda myrar
2. Organogena jordbruksmarker, d.v.s. dikad torvmark som används som jordbruksmark
3. Dikad skogsmark (lågproduktiv)
4. Gamla torvtäkter som ej brutits klart och lämnats utan efterbehandling

En typ av mark som inte explicit undersöktes, men som också har visat sig kunna vara en mycket stor källa till växthusgaser är återbeskogad jordbruksmark. Idag finns en ansenlig mängd nedlagd jordbruksmark där skog är planterad. Mätningar gjorda i Finland av bl.a. Lohila m. fl. (2004b) och Maljanen m. fl. (2004) visar att denna typ av mark kan ha betydande nettoavgång av såväl koldioxid som dikväveoxid.

Klimatpåverkan i det långa loppet beror också av hur man efterbehandlar marken och två olika typer av efterbehandling undersöktes för de olika torvmarkstyperna:

- återskapande av våtmark/myr
- beskogning

Klimatpåverkan uppskattades med hjälp av *radiative forcing*-modellering. Beräkningarna visar att utvinning av energitorv från orörda myrar på 200 års sikt resulterar i en klimatpåverkan som är ungefär lika stor som om man använt motsvarande mängd kol för energiproduktionen. Utvinning av energitorv från organogena jordbruksmarker ger en mindre klimatpåverkan än då orörda myrar tas i anspråk. Anledningen till detta är främst den snabba oxidation av torvlagret som sker på dränerad jordbruksmark. De undvikta metanemissionerna man tillgodoräknar utvinningen från orörda myrar ger ett betydligt mindre bidrag än de stora koldioxidavgångarna från dränerad jordbruksmark. Utvinning av energitorv från dikad beskogad torvmark kan enligt beräkningarna ge större eller mindre klimatpåverkan än de orörda myrarna främst beroende på den ursprungliga växthusgasbalansen. Vad gäller växthusgasbalansen på dikad beskogad torvmark så finns det mätningar som visar att den antingen kan vara en nettosänka eller en nettokälla för växthusgaser. Även för dikad beskogad torvmark är skillnaden jämfört med orörda myrar att man har en betydligt högre oxidationshastighet

av torvlagret. Utvinning av torv från gamla torvtäkter visade sig resultera i en klimatpåverkan som är ungefär lika stor som den från de orörda myrarna. Anledningen till detta är att metanemissionerna och avgången av koldioxid inte skiljer sig mycket mellan de gamla torvtäkterna och orörda myrar.

I denna studie har också gjorts en inventering där idag aktiva torvtäkter har klassats efter vilken typ av torvmark det var innan täktverksamheten startades. Producenter har tillfrågats om vegetationsbeskrivningar och annan dokumentation av täktområdena före verksamhetens start. De områden där beskrivning erhållits står för ca 50% av dagens svenska energitorvproduktion. Med hjälp av denna information och den tidigare beräknade klimatpåverkan från olika typer av torvmark har en uppskattning av klimatpåverkan från dagens energitorvanvändning i Sverige gjorts. Resultatet visar att klimatpåverkan på 300 års sikt från energitorvanvändningen är mindre än påverkan från kol men större än den från naturgas. Resultatet visar också att det finns en potential att minska dagens klimatpåverkan genom täktval. I denna studie har också beräkningar på klimatpåverkan från kontinuerlig användning av energitorv på ett sätt om motsvarar dagens produktion gjorts. Dessa beräkningar visar att klimatpåverkan från torvanvändningen ligger på en nivå mellan motsvarande värde för kol och naturgas. Som jämförelse finns även en beräkning av kontinuerlig användning av energitorv från dränerad och beskogad torvmark. Dessa två scenarier visar att vid kontinuerlig användning av torv fördröjs den positiva effekten av efterbehandlingen av täkterna. För enskilda täkter resulterar ofta efterbehandlingen i högre upptag av koldioxid och som därmed minskar klimatpåverkan från torven jämfört med användningen av kol eller naturgas.

Växthusgasbalansen för orörda myrar är ganska väl studerad och känd. Även växthusgasbalanserna på organogena jordar och dränerad skogsbevuxen torvmark är studerad i viss omfattning. De dränerade och skogsbevuxna torvmarkerna uppvisar dock olika, delvis oförklarade, egenskaper ur växthusgassynpunkt. Finska studier visar t. ex. att det kan förekomma en kolinlagring även i denna typ av mark, medan svenska studier har visat att dessa marker ofta är nettokällor men ibland nettosänkor för CO_2. Osäkerheten för denna torvmarkstyp är därför extra stor. Resultatet visar detta genom att spannet mellan max- och minvärdet för momentan (instantaneous) och ackumulerad *radiative forcing* är störst för denna torvmarkstyp. Vad gäller växthusgasbalanserna för tidigare torvtäkter så har inga tidigare studier hittats och resultaten för denna torvmarkstyp bygger helt på våra antaganden om analogier med andra torvmarker.

Växthusgasbalansen på den efterbehandlade ytan är också av stor betydelse och idag saknas kunskap om främst de återskapade våtmarkerna. Endast ett fåtal studier på t.ex. CH_4- emissioner och CO_2-upptag på sådana våtmarker finns tillgängliga och de sträcker sig endast över korta tidsperioder (ett par år). Hur CH_4-emissionerna och CO_2-upptaget förändras över tiden i dessa återskapade våtmarker vet vi lite om och det är också något som bör studeras närmare.

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1 Introduction

During the last couple of years there has been an intense debate concerning the climate impact and the classification of peat as an energy source. Internationally, peat is classified as a fossil fuel and in the EU ETS (European Union Emission Trading Scheme) energy producers using peat as fuel will have to hold emission allowances for emissions related to peat combustion. In Sweden the Peat Commission (Torvutred-ningen) SOU 2002:100 concludes that peat should not be put into a classification system since that might only conceal the complexity of its actual impact. The complexity is reflected by the properties of peat that clearly differ from both fossil fuels and renewable biofuels. The Peat Commission also concluded that energy peat has a place in a Swedish sustainable energy system. At present, electricity produced in combined heat and power plants using peat qualifies for green certificates (along with electricity produced by using biofuels, wind or other renewable energy sources). These very different viewpoints of the use of energy peat make the question of the current climate impact of the use of energy peat and how the impact can be limited a topic of interest.

2 Objective of the study

A number of compilations and simulation studies of the climate impact of the use of peat for energy production have been performed during the last 10 years (e.g. Savolainen et al., 1994; Rhode & Svensson, 1995; Zetterberg & Klemedtsson, 1996; Åstrand et al., 1997, Crill et al 2000 and Uppenberg et al., 2001).

The objective of this study was to calculate the climate impact of the current use of energy peat in Sweden and to investigate the potential to reduce greenhouse gas emissions by choosing harvesting site and after-treatment. Four different types of peatlands used for harvesting have been investigated:

1. pristine mires
2. mires drained and used for agriculture
3. mires drained and used for forestry
4. mires previously used for peat harvesting (not after-treated)

Descriptions of land-use and vegetation cover before the start of harvesting of the presently used peat-harvesting areas were collected in order to classify and estimate the climate impact of currently used harvesting sites.

A scenario showing the climate impact of the continuous utilisation of energy peat was also calculated.

3 Structure of this study

In the following three chapters the methodology and the systems studied are described. Chapter 6 describes the specific assumptions and methodology used for calculating the radiative forcing of the currently used peat harvesting areas. In chapter 7 - 10 the specific assumptions for determining the radiative forcing of the four peatland types studied are given. These assumptions include emissions and uptake of greenhouse gases (CO_2, CH_4 and N_2O) during the different stages of peat harvesting as described by Table 5.1. In chapters 11 and 12 the results of the calculations of the radiative forcing are given. Chapter 11 is structured by four sections each presenting the result of one of the specific peatland types (pristine mire, mires drained for agriculture, mires drained for forestry or old peat harvesting sites). Six figures are given in each section, three for each of the two aftertreatment methodologies (re-wetting or afforestation). The presented values are accumulated emissions, instantaneous radiative forcing and accumulated radiative forcing. In some of the sections there are extra figures showing the sensitivity of a specific parameter. In chapter 12 we present the total climate impact of peat utilisation at presently used harvesting sites in Sweden, expressed as radiative forcing. The impact of continuous peat utilisation at the same production level is also given, assuming the same harvesting practice as today (e.g. 20 year harvesting period) and use of the same peatland types (as far as known today). In the discussion there are sections discussing both the results and the uncertainties of the assumptions made for each of the peatland types. At the end of the discussion the uncertainties of the general assumptions are discussed.

4 Methodology

In this study we approximated the climate impact of peat utilisation by using the concept of radiative forcing (Zetterberg, 1993). The solar radiation absorbed by the Earth, i.e. the surface and atmosphere, is balanced at the top of the atmosphere by outgoing planetary radiation. A change in the net radiation at the tropopause[1] caused by either a change in solar radiation or planetary radiation is defined as radiative forcing and is measured in W/m^2 (instantaneous radiative forcing) or J/m^2 (accumulated radiative forcing). Greenhouse gases effectively absorb the outgoing planetary radiation and a change in the atmospheric concentration of those gases will lead to a change in the radiation balance, i.e. radiative forcing. A positive radiative forcing tends to warm the surface of the earth and a negative radiative forcing tends to cool it.

[1] The tropopause is the boundary layer between the lower part of the atmosphere, known as the troposphere, and the overlaying stratosphere.

The relation between radiative forcing, emissions of greenhouse gases and climate impact can be simplified by the following: emissions will lead to an increase of atmospheric concentrations which will result in a radiative forcing (change in radiative balance) which will lead to a change in temperature, hence a climate change. In this study we used the concept of radiative forcing and hence only the potential climate impact was calculated. For a more detailed description of the concept of radiative forcing see Zetterberg (1993).

There are also other estimates of potential climate impact in use. The IPCC, Intergovernmental Panel on Climate Change, recommends that the GWP-concept (Global Warming Potential) should be used to calculate and compare greenhouse gas emissions on national and international level. The GWP-indexes for different greenhouse gases are defined as the cumulative radiative forcing during a defined time period, caused by a unit mass of gas emitted at the beginning of the time period, expressed relative to some reference gas (usually CO_2).

In this study most calculations were be done by using radiative forcing but some comparisons were made by using the GWP-concept. The reason for mainly using radiative forcing is:

- Radiative forcing can describe the impact of an emission scenario that stretches over a long time, this can not be done by using GWP.
- GWP is a relative measure. A GWP today is not the same as a GWP in 2100.
- According to model studies performed by the IPCC, there seems to exist a direct relation between radiative forcing and global average temperature (hence a good measure of the potential climate impact).

The equations used for calculating the radiative forcing due to an increase in concentration of greenhouse gases used in this study are the ones presented in Ramaswamy et al. 2001 (Table 6.2). Since the calculations made in our study concerns small changes in concentration and the radiative forcing is calculated per square meter of harvesting area, the equations describing the radiative forcing were approximated by the derivatives of the equations presented in Ramaswamy et al (2001). For an explanation of this methodology see Zetterberg 1993.

5 System description and assumptions

In this study the measure of (potential) climate impact, radiative forcing, was modelled based on the emissions/uptake of carbon dioxide, methane and nitrous oxide. The exchange of those gases from the different stages of the production of energy peat was considered. Since the study concerns the anthropogenic impact, the radiative forcing was calculated as a relative measure of the emissions caused by the peat harvesting, combustion and aftertreatment of cutaway area and the emissions/uptake at the initial mire. Table 5.1 below summarises the different stages of the energy peat production chain that were considered in this study.

Table 5.1 Stages of energy peat production.

Stage	Year	Description
Pristine mire	before year 0	The mire has not yet been affected by activities connected to peat harvesting.
Drained mire, before harvesting	0 –5	During year 0, the covering vegetation is stripped off and ditches are made on the extraction area, approximately 20 m apart from each other. The area is drained to lower the water content from 90-95% to 80-85 %. This will normally take 1 – 5 years. We assume 5 years[2].
Harvesting, transport and combustion of peat This	6 – 25	When the water content has been lowered enough for the ground to carry the machines, harvesting of peat can start. can be done either as milled peat or as sod peat. The extracted peat is dried lying in the field, and thereafter transported to large storage piles close to the extraction area. The peat harvesting is carried out during the summer months During the winter months, peat is transported directly from the storage piles to plants for heat/power production.
After-treatment	26 -	When the peat harvesting has been finished after approximately 20 years, the area can be converted to agricultural land (not common in the modern peat industry) or forest, or it can be restored to new wetland.

The emissions during the different stages of the production were considered in the following way:

Emissions in scenario =
emissions/uptake during drainage + emissions/uptake during harvesting period + emissions due to combustion + emissions/uptake at the site after harvesting has ceased (after-treated site) – emissions/uptake from original state (pristine mire, agricultural field, drained forest or old harvesting site).

This means that the radiative forcing simulated in each of the scenarios represents the anthropogenic impact due to the harvesting and combustion of the peat compared to leaving the pristine mire (or agricultural field or drained forest or old harvesting site) as

[2] During the drainage period most sites will have a higher rate of oxidation than the undrained mire but lower emissions of CH_4. At pristine mires the effect of increased CO_2 emissions is larger than the effect of lower methane emission resulting in higher net emissions of greenhouse gases. At agricultural peat soils and drained afforested peatlands this increase of greenhouse gas emission during drainage is smaller. Using a drainage period of five years instead of a shorter period will have some impact on the results but it will not be significant due to the short period.

it is. We refer to the initial state of the peatland as the reference case. The four reference cases used in this study were:
Pristine peatland – the peatland will remain unaffected by direct human impact.
Agricultural field – the field will continuously be used for agriculture.
Drained forest – the forest will continue to grow until mature.
Old harvesting site – will either remain in a growing re-wetted state or remain in a drained state where rapid oxidation of peat is occurring.
The reference cases are further described in each of the sections of different peatland scenarios below.

The following assumptions for peat characteristics and impact area were used in this study:

- The area affected by drainage was assumed to be twice the size of the extraction area. The drained area that is not used for harvesting, here named the surrounding area, is used for e.g. storage piles and access roads. Based on this assumption, every m^2 of mire that is used for peat harvesting will cause 1 m^2 of drained surrounding area (personal communication L-E Larsson, 2004, Nyström 1992). This is the same assumption made in many of the previous studies of the climate impact of energy peat utilisation e.g. in Uppenberg et al 2001, Rodhe & Svensson 1995 and Zetterberg & Klemedtsson 1996. In Åstrand et al 1997 the surrounding area (the area affected by drainage but not harvesting) was assumed to be 90% of the extraction area. (In Savolainen et al. 1994 this aspect is not considered). The underlying fact for this assumption is that the circumference ditches have an effect approximately 10-20 m in each direction, meaning that land area of 10-20 meters outside the harvesting area are affected by the drainage (personal communication L-E, Larsson, 2004). Of course, the proportion of surrounding area to the extraction area is dependent on both size and spatial distribution of the harvesting area. The morphomethry of mires differs depending on mire type. The bog type, more common in the southern parts of Sweden, are generally more evenly geometrically shaped while the northern types will more often have an uneven geometric shape. Since no data on this matter was found the assumption of the size of the surrounding area made in previous studies was used.

- In this study the average peat depth at the harvesting area was set to 2.1 m (mineable 1.9 m). The assumed value was based on the average value given by nine producers. According to Franzén (1985) the average peat depth on all Swedish peatlands is 1.7 m. However, it seems reasonable to assume that peatlands used for peat harvesting have deeper peat layer than the average, which also indicates that the value assumed in this study lie within a reasonable range.
  In Uppenberg et al. (2001) the average mineable depth is assumed to be 1.4 m. According to L-E, Larsson (personal communication 2004) the average mineable depth is probably deeper than 1.4 m. At the beginning of modern peat harvesting in Sweden (early of 1980s) it was not considered profitable to extract peat from areas

with a shallower peat depth than 1.5m. It should be noted that there is a great local variation of peat depths and the estimation of average peat depth on a mire include a considerable amount of uncertainty.

- The average peat depth at the surrounding area was assumed to be half of the depth at the extraction area. This assumption was not based on any measurements but is a qualified guess. It is reasonable to assume that there is also some peat in the surrounding soil, although there might be exceptions where the ditches are made close to a border of mineral soil. However it is not likely that the peat layer is as deep as at the extraction area. In previous studies, i.e. in Uppenberg et al (2001) & in Åstrand et al (1997) it has been assumed that the oxidation of peat at the afforested surrounding area after the peat harvesting will continue at a relatively low rate (300g CO_2/m^2a^{-1}) throughout the study period (100-500 years). At this rate of oxidation and a peat depth approximately half of the peat depth at the extraction area this means that the oxidation will continue for ~450 years. In our study we also have scenarios where the oxidation rate at the surrounding area have been assumed to be significantly higher than 300 g CO_2/m^2a^{-1} and that means that the peat layer will have oxidised completely at an earlier stage.

- Peat energy content per extraction area: To estimate the average energy content per m^2 of Swedish mires used for energy peat production the following assumptions were used, (for details on data sources, see below). The average energy peat has moisture content of 45%, a density of 330 kg/m^3 and a net calorific value of 10.28 MJ/kg (as delivered). In accordance with earlier estimates by L-E Larsson (personal communication, 2004) it is assumed that approximately 2 m^3 of peat in undrained state is required for the production of 1 m^3 energy peat (45% moisture content). Note that these calculations only include the extraction area and not peat in the surrounding area that may be affected by the peat extraction. We assume that the extraction period is 20 years and the approximate energy content per m^2 and year at the peat extraction area is then150 MJ/m^2 a.
  The assumptions made by Uppenberg et al. (2001) are: peat depth = 1.4 m, net calorific value (NCV) = 20 MJ/kg (dry substance), harvesting period = 20 years, peat density = 1000 kg/m^3 (field conditions), moisture content = 92% (field conditions). The assumptions result in an extracted amount of peat of 112 MJ/m^2a during 20 years. According to Statistics Sweden the bulk density of energy peat is 300 kg /m^3 (moisture content ~45%). Wall (1998) gives the following properties for different types of energy peat qualities:
  milled peat: moisture content 50-55%, NCV = 2.3 kWh/kg (8.4 MJ/kg), density 300 kg/m^3.
  Sod peat: moisture content 35%, NCV = 3.5 kWh/kg (12.5 MJ/kg), density 320-350 kg/m^3.
  Peat bricks: moisture 10-12%, NCV = 4.7 kWh/kg (17 MJ/kg), density 600-700 kg/m^3.

- In many of the figures where the results of the calculations are presented also values for coal and natural gas is given. Those values were also calculated and were based on the emission factors presented in Table 5.2, based on Uppenberg et al (2001).

Table 5.2. Emission factors for coal and natural gas.

Fuel	CO_2 [g CO_2/MJ]	CH_4 [g CH_4/MJ]	N_2O [g N_2O/MJ]
Coal	94.2	1.1	$12\cdot10^{-3}$
Natural Gas	59	$2.8\cdot10^{-3}$	$5.6\cdot10^{-4}$

In the peat scenarios the emissions associated with harvesting machinery and transports were included. The following estimates of greenhouse gas emissions were used.

CO_2 emissions
The emissions from working machines and transports are estimated to 1 g CO_2/MJ of extracted peat according to Uppenberg et al. (2001) and that value has also been used in this study.

CH_4 emissions
The emissions of methane from working machines and transport are small but have been estimated to 0.7 mg CH_4/MJ (based on an energy demand of 1.3% of the extracted peat as diesel oil) by Uppenberg et al (2001).

N_2O emissions
The emissions of nitrous oxide from working machines and transports are small, but have been estimated to 0.025 mg N_2O/MJ (based on an energy demand of 1.3% of the extracted peat as diesel oil) by Uppenberg et al (2001).

6 Swedish peatlands in use for production of energy peat

Today there are approximately 100 active peat-harvesting areas in Sweden where energy peat is extracted (SST, 2004). In this study an attempt was made to determine the original peatland type of the harvesting sites before the start of the current activity. Producers were contacted and answered by giving vegetation descriptions, often made in connection with the application for concession, of the sites. The mires/peatlands used in the Swedish production of energy peat today have different histories. Some of them were pristine mires before the harvesting started, while others were already affected by earlier drainage. The reason for this drainage could have been to increase forest productivity, to use the land for agriculture or other purposes.

The emissions before, during drainage, during harvesting and after harvesting (with aftertreatment) were estimated in this study for each of the different categories of peatlands by consulting present literature and researchers (see chapters 7 - 10). The climate impact from each type was determined by modelling the radiative forcing over the whole utilisation chain. The impact from the Swedish energy peat production was then determined by using weight factors of the amount of peat produced at the sites. An assessment of the land-use history of each peat harvesting area was performed since no study of the land-use history of the peatlands that are in use for peat harvesting was available. Hence, it was not known how many peat-harvesting areas that originally were pristine mires, drained for agricultural purposes, drained for forest production etc. Chapter 6-10 below describes the different categories of peatlands that are used or could be used for peat harvesting in Sweden and the estimated greenhouse gas fluxes from those sites during the different stages of peat harvesting. In chapter 12 the results of the assessment of the land use history of the today used peat-harvesting areas are given, which will give an indication of how common the different peatland categories are among the present harvesting areas.

7 Natural peatlands

This category includes peatlands that have not been subject to human impact before the drainage for peat extraction. Natural peatlands can be quite large sources of methane emissions. Methane production is closely connected to the presence of anoxic conditions (no oxygen) which is the case in many of the wet natural peatlands. When a peatland is drained the anoxic zone is limited and the increased oxic zone in the surface layer will help the oxidation of methane to carbon dioxide. Hence draining a peatland will reduce the methane emissions. On the other hand the limited decomposition of organic material due to the lack of oxygen in the natural mire will change when drained and decomposition processes will increase, resulting in larger emissions of carbon dioxide.

In the scenarios for natural mires the reference case will be that the mire remains unaffected by human impact.

7.1 Before harvesting – pristine mire

7.1.1 Carbon dioxide

Pristine peatlands represent an average sink of atmospheric CO_2 during Holocene. The average values of CO_2 accumulation of a peatland can be estimated by measuring peat depth and determining the age of the mire. However, due to increasing amount of accumulated carbon the source of anaerobically mineralised CO_2 at the mire increases with time. Simultaneously the potential net primary production at the minerotrophic

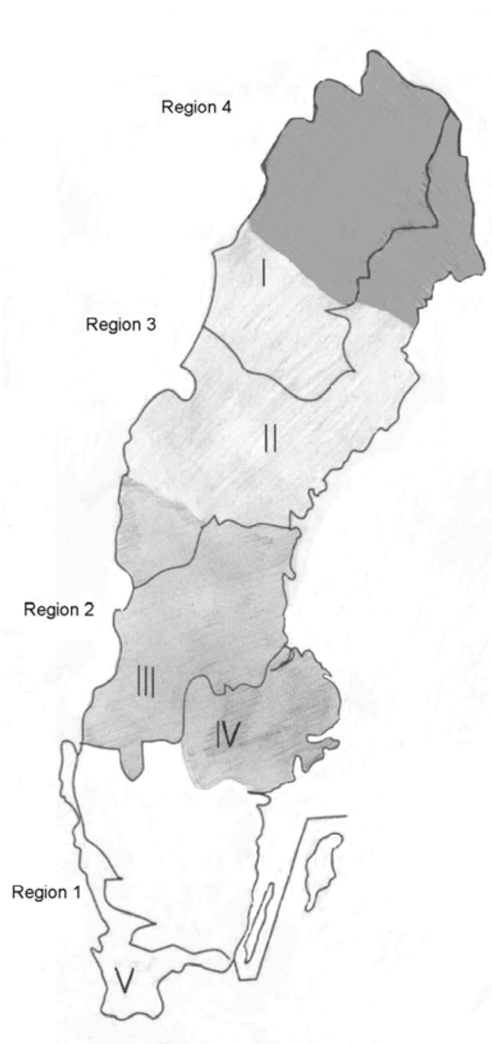
mire surface decreases due to decreased input of mineral nutrients from the surrounding catchment. These two effects together result in a current carbon accumulation rate considerably lower than the Holocene average (Klarqvist 2001 and references therein). Note that Klarqvist (2001) does not include lateral growth of the mire. No data on current CO_2 uptake at mires due to lateral growth has been found, but the effect is known to have been of great importance historically. Direct estimates of the current annual exchange of CO_2 between mires and the atmosphere are also very limited. Therefore the estimated current CO_2 exchange between mires and the atmosphere are most uncertain and the long-term Holocene averages should be considered as representing an upper limit. The report by Kasimir-Klemedtsson et al (2001) is an overview of greenhouse gas emissions from Swedish peatlands of different land-use where the following values based on Turunen & Tolonen (1996) are used for carbon dioxide uptake in pristine mires in Sweden.
Bogs = 77 g CO_2/ m^2a
Fens = 51 g CO_2/ m^2a
Mires = 62 g CO_2/ m^2a[3]

In this study the differentiated values compiled by Kasimir-Klemedtsson et al (2001) were used for most scenarios, there are also scenarios assuming a lower level of initial CO_2 uptake.

7.1.2 Methane

The methane emissions from natural mires have been investigated by Nilsson et al (2001). In that study the classification of mires into eight classes, described by the composition of the ground vegetation, according to Hånell (1998) was used. According to previous studies only four of these classes emit methane. In the investigation conducted by Nilsson et al (2001), the mires were also divided into different geographical regions. Figure 7.1 show the location of these regions, from Region 1-V in the south to region 4-I in the north of Sweden.

[3] Mires here refer to peatlands that do not emit methane according to Nilsson et al (2001).



Most average methane flux rates for a certain mire vegetation type were not statistically different at $p<0.05$ between regions (Nilsson et al., 2001). The estimated regional average flux rates spanned however quite often a large range, often significantly different at higher p-values ($p<0.1$). Therefore mire type flux rates specific to each region has been used in this study.

From the history of the present peat harvesting sites, the ones that were pristine mires before the start of harvesting could be classified as belonging to one of the three groups given below:

- Tall sedge – (fen) dominated by tall sedge fen species such as *Carex rostrata*, *Carex chordorrhiza, Carex lasiocarpa*, *Menyantes trifoliata*, and *Eriophorum angustifolium*.
- Marsh *Andromeda* – (bog) dominated by *Sphangum fuscum* and other species as *Cladonia spp*., *Andromeda polifolia*, *Empetrum nigrum, Calluna vulgaris* and *Vaccinium*.
- Low sedge- (fen) dominated by low sedge fen species such as *Carex limosa*, *Carex pauciflora*, *Scirpus caespitosus* and *Eriphorum vaginatum.*

Figure 7.1. The regions of this study.

These groups represent three of the methane emitting classes as described by Nilsson et al 2001. The fourth class is transitional fen but non of the identified mires fitted into this class and it constitutes only three percent of the area of open mires[4] in Sweden (Nilsson et al 2001). In this study methane emissions from the different types of pristine mires resulting from the field measurement campaign in 1994, together with corrections for inter-annual variation and wintertime flux Nilsson et al (2001) were used in the different scenarios. We used median flux values for each mire type and region. Average values

[4] Open mires are those with a peat depth < 30 cm and a forest productivity < 1 m^3sk/ha a^{-1}.

are the best estimates for entire populations and also correct estimates for individual samples from a population if normal distribution can be assumed. However, for skewed distributions, the median value is a more probable estimate for individual samples. The populations of methane flux rates of the studied mires are very skewed, and the most probable flux rate of an individual mire is therefore the median value (B. Ranneby pers. com., 2004). Since the mires used for peat-harvesting in Sweden is a very small sample from the total population of Swedish mires the median values are the most accurate estimate.

Tall sedge mires

According to the study made by Nilsson et al (2001) high values of the methane emissions from tall sedge mires are observed in region 3-I. This type is a very common mire type in all regions of the country. The variation in measured methane emissions is high The data given in Table 7.1 below are based on the measurements made by Nilsson et al (2001) indicates differences both in mean and median fluxes. The annual average and median values are adjusted for winter fluxes and inter-annual variation.

Table 7.1. Measured methane fluxes from tall sedge mires in different regions.

Region	Flux CH_4 average [g CH_4/m^{2}a]	Flux CH_4 average [mg CH_4/m^2 day]	Flux CH_4 median [mg CH_4/m^2 day]	Flux CH_4 median [g CH_4/ m^{2}a]
Region 1	8	111	38.8	2.8
Region 2	17.4	45.8	29.6	11.2
Region 3-I	81	238	67.5	23.0
Region 3-II	19.4	57	30.6	10.4
Region 4-I	30	105	23.6	6.8
Region 4-II	21.8	75.7	56.4	16.2

Two scenarios have been made for tall sedge mires. One with a high value, 23 g CH_4/m^2a^{-1} representing region 3-I, and one with a medium value of 10 g CH_4/m^2a^{-1} representing region 2 and 3-II.

Low sedge mires

The difference of methane flux from low sedge mires in different regions seemed to be large. We identified objects of low sedge type that today are under peat harvesting in region 4-I and region 2. The values of methane fluxes given in Table 7.2 are values from Nilsson et al (2001) adjusted for winter fluxes and inter-annual variations.

Table 7.2. Methane fluxes from low-sedge mires

Region	Flux CH_4 average [g CH_4/m^{2}a]	Flux CH_4 average [mg CH_4/m^2 day]	Flux CH_4 median [mg CH_4/m^2 day]	Flux CH_4 median [g CH_4/ m^{2}a]
Region 1-V	8.6	20.1	9.6	4.11
Region1-IV	13.2	30.6	14.8	6.38
Region 2	11	29.2	14.4	5.42
Region 3-I	18	52.9	27.3	9.29
Region 3-II	12.4	36.2	16.2	5.55
Region 4-I	24	82.3	70.9	20.68
Region 4-II	35.2	122.2	67.8	19.53

The median values for region 4-I and 4-II are quite similar and a simulation with a methane flux of 20 g CH_4/m^2a^{-1} was made representing these regions. The value for the rest of the regions was represented by a scenario with a methane flux from the pristine mire of 6 g CH_4/ m^2a^{-1}.

Marsh *Andromeda* mires

This mire type amounts to 8% of the total mire area in Sweden (Nilsson et al 2001). However, the abundance of this type differs significantly with region. It amounts to 32, 20, 3 and 3% in region 1-4 respectively. For this reason scenarios were only made for mires in region 1 and 2. The value of methane emissions used in region 1 was 8 g CH_4/m^2a^{-1} and for region 2 was 3.5 g CH_4/m^2a^{-1}. The values of methane emissions given in Table 7.3 are taken from Nilsson et al (2001).

Table 7.3. Methane fluxes at Marsh/*Andromeda* mires in different regions

Region	Flux CH_4 average [g CH_4/m^{2}a]	Flux CH_4 average [mg CH_4/m^2 day]	Flux CH_4 median [mg CH_4/m^2 day]	Flux CH_4 median [g CH_4/m^{2}a]
Region 1-V	5.8	13.7	14.8	6.27
Region 1-IV	19.4	45.2	20.2	8.67
Region 2	5	13.3	9.3	3.50
Region 3	5.4	15.8	5.3	1.81
Region 4	6.2	21.3	11.9	3.46

Summary of CH_4 emissions from pristine peatlands

The table below summarises the scenarios that were used for pristine mires. For each of the six combinations of mire type and methane flux different aftertreatment methods are applied. Two aftertreatment methods were chosen, rewetting and afforestation.

Table 7.4. Values on CH_4 emissions from pristine peatlands

Mire type	Region	Flux
Low sedge	4-II & 4-I	20 g CH_4/m^2a
	Other	6 g CH_4/m^2a
Tall sedge	3-I & 4-II	23 g CH_4/m^2a
	2 & 3-II	10 g CH_4/m^2a
Marsh/Andromeda	1	8 g CH_4/m^2a
	2	3.5 g CH_4/m^2a

7.1.3 Nitrous oxide

According to the compilation of greenhouse gas fluxes from different peatlands in Sweden made by Kasimir-Klemedtsson et al. (2001) the emissions of nitrous oxide from pristine mires are assumed to be negligible. However, von Arnold et al. (2004c) presents a value of N_2O emissions from an undrained tall sedge mire to be 20-30mg/m^2a. In this study the value 20 mg/m^2a was used for all pristine mires.

7.2 Drained mire, before harvesting

7.2.1 Carbon dioxide

In Uppenberg et al. (2001) the carbon dioxide emissions from drained natural peatlands are represented by a worst case estimate of 1000 g CO_2/m^2a. That assumption is based on measurements made by Sundh et al (2000) on CO_2 emissions on drained peatlands in Sweden with vegetation cover removed. Measurements were made at six different sites, three in the northern parts and three in the southern parts of Sweden. The average value[5] estimated by Sundh et al (2000) is 0.23-1.0 kg CO_2/m^2a. Similar values have been measured in Finland by Nykänen et al. (1996). In our study a linear increase (0-1000) was assumed from year 0-3 and the emissions were thereafter assumed to stay at the level of 1000 g CO_2/m^2. The same assumption for the extraction and the surrounding area was made during the first five years of drainage before the actual harvesting starts. The increased growth of trees and other vegetation on the surrounding area increasing the CO_2 uptake due to the drainage can be assumed to be small during this first short period and was therefore ignored.

[5] Note that the values given in Sundh et al (2000) are calculated total emissions during the growing season.

7.2.2 Methane

Extraction area

The decrease of methane emissions due to drainage is highly dependent on how well the ditches are managed (Sundh et al, 2000). If the ditches are held clean from vegetation the methane emissions can be kept at a low level. The decrease in methane emissions is also smaller for mires with lower original emissions (Sundh et al 2000). In this study the assumption made was that the area weighted (the methane emitted from the ditches recalculated to originate form the total mire area) methane emissions decrease to 10% of the original value. However, the methane emissions were not assumed to decline to values below 1.5 g CH_4/m^2a.

Surrounding area

Uppenberg et al. (2001) assumed the methane emissions from the surrounding area to be somewhat higher than from the extraction area, i.e. 25% of the original emissions due to poorer maintenance of the ditches. These assumptions are based on Sundh et al. (2000) and Nykänen et al. (1996). In our study the same assumptions as in Uppenberg et al. (2001) was used for mires with originally high methane emissions. However, we assumed that the methane emissions will not decline to values below 3.0 g CH_4/m^2a, hence this value was used for mires with initially low (< 10 g CH_4/m^2a) methane emissions.

7.2.3 Nitrous oxide

The emissions of nitrous oxide from natural mires are negligible according to Kasimir-Klemedtsson et al (2001) but nutrient rich sites drained for forestry can produce N_2O at rates from 0.08-0.22 g N_2O/m^2a according to (Nykänen et al 1996) and between 0.08 – 0.9 g N_2O/m^2a according to von Arnold et al (2004a) & (2004c). These values would therefor be valid for the first phase (i.e. the drainage before harvesting) of peat harvesting areas. However the fluxes might be even higher since the drainage for peat harvesting is more efficient than the drainage for forestry (Nykänen et al 1996). The emission value for the drainage period before start of harvesting used in this study was the average value according to Nykänen et al (1996), 0.15 g N_2O/m^2a.

7.3 During harvesting

Investigations of greenhouse gas emissions from peat-harvesting areas have been made both in Sweden (Sundh et al 2000) and in Finland (Nykänen et al 1996) and many of the assumptions made in our study are based on those measurements.

7.3.1 Carbon dioxide

Extraction area. In Sundh et al. (2000) measurements of carbon dioxide fluxes from active peat harvesting areas in Sweden are reported. Those measurements show that the average emissions of CO_2 was 0.23-1.02 kg /m^2a, with a mean value of 600 g/m^2a during the growing season. The mires investigated were all pristine mires before the harvesting started. In Uppenberg et al. (2001) the carbon dioxide emissions are estimated by using the maximum value of the range, i.e. 1000 g CO_2/m^2a during the harvesting period (year 6-25, i.e. 20 years), and it also includes the emissions from stockpiles and other losses. According to Nykänen et al 1996, the estimated emissions from stockpiles are 175 g /m^2a. It should be noted that this value is only based on measurements during half of the year (growing season), it is most likely that oxidation occur in the stockpiles also during winter, and hence this value should be seen as a value in the lower range. Approximately 6% of the carbon in the mire is lost to the atmosphere due to microbial decomposition during harvesting (Sundh et al 2000). In this study that loss was considered when determining the amount of extracted peat per m^2 of extraction area.

Since the average value measured by Sundh et al (2000) only includes emissions during the growing season and not emissions from stockpiles we assumed a value in the upper range. We assumed that the emissions of CO_2 during the harvesting period are 1000 g CO_2/m^2a.

Surrounding area. In Uppenberg et al. (2001) the surrounding area is assumed to have lower emissions of carbon dioxide than the extraction area due to less working of machines and the increasing growth of trees and other vegetation. In this study the CO_2 emissions were assumed to stay high during the first five years of harvesting and then decrease linearly from 1000 to 300 g CO_2/m^2a during year 11-25. Uppenberg et al. (2001) considered the increased growth of forest on the surrounding area to be negligible and the emissions from stockpiles included in the high CO_2 emission value. In this study the decrease of net CO_2 emissions from the surrounding area were considered to be the result of both a decrease in the oxidation rate of the peat and an increase in uptake due to the increasing growth of trees and other vegetation.

7.3.2 Methane

Extraction area: According to Sundh et al. (2000) the emissions of methane from the extraction area during the growing season were 0.41-4.5 g CH_4/m^2a. The emissions mainly origin from the ditches and can most probably be avoided by keeping the ditches clean from vegetation. In this study we assumed that the methane emissions from the extraction area stay constant during the whole harvesting period (20 years). The level of methane emissions during harvesting is assumed to be the same as during the drainage period before harvesting (10% of methane emissions from pristine mire, but not lower than 1.5 g CH_4/m^2a).

Surrounding area: Before the extraction of peat the surrounding area is assumed to have higher emissions of methane than the harvesting area. This is the assumption also when the harvesting starts, but after a few years the emissions start to decrease due to the increased tree growth. The emissions are assumed to decrease to 0 by year 8 and thereafter stay at that level.
The emissions of methane from working machines and transports are small, but are estimated to amount to 0.7 mg CH_4/MJ (based on an energy demand of 1.3% of the extracted peat as diesel oil, Uppenberg et al 2001). These emissions were in this study considered together with the emissions from the combustion.

7.3.3 Nitrous oxide

Extraction area: In the Finnish study, Nykänen et al. (1996), of greenhouse gas emissions from peat harvesting areas, nitrous oxide is included. According to that study the nitrification activity and availability of nitrate are important factors to regulate production of N_2O in peat soils. Furthermore, Nykänen et al (1996) stated that the emissions of N_2O from natural mires are negligible but that nutrient rich sites drained for forestry can produce N_2O rates between 0.08-0.22 g N_2O/m^2a. Nykänen et al (1996) studied two different peat-harvesting sites including areas of newly opened and older harvesting areas as well as a cut-away site. Nitrous oxide emissions from the most nutrient poor site were close to the detection limit. At two of the peat harvesting areas the annual emissions were 0.08 mg N_2O/m^2a, which is typical for forested peatlands. According to Nykänen et al (1996) the N_2O emissions were highest from recently started harvesting areas and old sites where the peat and clay had mixed. The abandoned area emitted some N_2O, but less than the younger area still used for peat harvesting. It was assumed in our study that for the extraction area the emissions decrease to 0.1 g N_2O/m^2a by the tenth year of harvesting and then increases again to 0.15 g N_2O/m^2a by the end of the harvesting period.

Surrounding area: In our study the emissions were assumed to decrease linearly during the first five years of harvesting to 0.08 g N_2O/m^2a, the typical value for forested peatlands according to Nykänen et al (1996).

7.4 Combustion

The same values on emissions of the three greenhouse gases due to combustion were used in all scenarios for all types of mires, i.e. pristine mires, organic soils (agricultural peatlands), drained forests and old harvesting areas.

7.4.1 Carbon dioxide

The CO_2 emission factor for combustion of Swedish energy peat has been updated by Nilsson (2004). The Swedish national average value is close to the international value given by IPCC (106 g CO_2/MJ). As determined by Nilsson (2004), the value of the emission factor is dependent on the moisture content of the peat. At lower moisture contents higher amounts of energy can be retrieved (per tonne peat). Today only 20% of the combusted Swedish energy peat consist of significantly drier peat such as peat bricks. Therefore, in this study we used an emission factor of 105.2 g CO_2/MJ, which is valid for energy peat with an approximate water content of 45%[6]. An oxidation factor of 0.99 was used. These assumptions resulted in the CO_2 emission factor being 104 g CO_2/MJ.

7.4.2 Methane

The CH_4 emissions from combustion of peat have been estimated to 0.005 g CH_4/MJ in Uppenberg et al 1999. This value is an average value for Swedish power/heat plants using peat and the value was used in our study.

7.4.3 Nitrous oxide

The amount of emissions of N_2O from combustion of peat depends a lot on the technology used. If fluidised bed combustion (FBC) is used, the emissions will be ten times higher (0.04 g CH_4/MJ compared to 0.004 g CH_4/MJ peat) than for other techniques. The N_2O emissions from combustion of peat were estimated to 0.006 g N_2O/MJ in Uppenberg et al. (1999). This value, which is an average value based on the size and types of combustion plants in Sweden, was used in our study.

7.4.4 Combustion of peat bricks

In Sweden there is a considerable amount of dry peat-bricks (moisture content 8-10%) being used at peat fed heat and power plants. Since lower moisture content corresponds to a lower CO_2 emission factor one could argue that for some of the combusted peat a lower CO_2 emission factor should be used. However, if including the peat bricks in this study, which includes emissions from all stages of peat production and combustion, one would also have to consider the method of drying the peat. If the drying method not is CO_2 neutral that would also have to be considered in the model. When considering the peat bricks it is also important to note that the peat bricks manufactured in Sweden actually contain 70% peat and 30% wood and are all made at the HMAB factory in

[6] Energy peat is usually dried in the field and stored in stockpiles. Depending on weather conditions the moisture content of field-dried peat will vary between 35-60%.

Sveg. The production at the HMAB factory in Sveg has amounted a considerable part of the total energy peat production in Sweden but has declined in recent years. One of the main reasons for the decline in production is competition from other countries and less buyers. In 2003, 736 GWh peat bricks were delivered from Sveg. In the same year the total energy peat production in Sweden amounted to 2663 GWh. Considering that the peat bricks only contain 70% peat, the amount of the total Swedish production that end up burned as peat bricks will be ~20%. Considering that 20% of the actually burned peat is significantly drier than 45% would according to Nilsson (2004) result in a reduction of the emission factor from 105 to 103 g CO_2/MJ. Since the relative difference is small (~2%) and the CO_2 emissions from the production of the peat bricks are not included (that might counteract the use of a lower emission factor), a lower emission factor was not considered.

7.5 Aftertreatment

In this study the climate impact following two different types of aftertreatment was determined; afforestation and rewetting. For the extraction area it is assumed that the original mire type or land use have no impact on the emissions regime after the harvesting has been terminated. This since we assumed that a sufficient amount of the peat is removed and that the new land use will be more dependent on climatic and hydrological conditions of the site. For the surrounding area, where no peat has been removed (observe that the peat layer was assumed to be half of the thickness at the extraction area), the history of land-use will be of importance.

7.5.1 Restoration of wetland

Gorham & Rochefort (2003) conclude that wetland restoration after peat harvesting have been studied over much to short periods of time to ensure progression to, or even well toward, a fully functional peatland reasonably compatible with the pristine state of similar peatlands elsewhere. Further it is stated that long-term monitoring of peatland-restoration projects is essential for a better understanding of how to carry out such restoration successfully.

In Waddington & Warner (2001) CO_2 emissions from a restored and a naturally restored, (i.e. by natural succession) cut-away peatland have been measured. The results show that the restoration does not return the net carbon sink function of the mire. However, the investigated site had a remaining peat depth of approximately 1.7 m which is far more than what was assumed to be left at the extracted sites in this study.

7.5.1.1 CO_2 emissions

Since no new data on re-wetted cut-away peatlands has been found, the same assumptions as in Uppenberg et al (2001) was made in this study. The assumption is that the CO_2 uptake will increase linearly during the first five years after restoration to 363 g CO_2/m^2a and thereafter stay constant throughout the study period. This value is based on a number of studies of peat layers in old peatlands but only one of these actually measured current net exchange in newly restored wetlands (Tuittila et al 1999). Tuittila et al (1999) concludes from a two-year study that already after a few years a re-wetted site can function as a carbon sink.

7.5.1.2 CH_4 emissions

According to Tuittila et al (2000) it will take time before the CH_4 emissions of a re-wetted site will reach the levels of the pristine mire. This delay includes among other things the slow recovery of the methanogenes due to a long period of dry conditions. During dry years, lower methane emissions also from pristine mires are observed due to less favourable conditions for the methanogenes and the effect usually lasts during the next-coming season as well (Tuittila et al 2000). The study conducted by Tuittila et al (2000) lasted for three years, one year before rewetting and two years after. During the two years after rewetting an increasing trend of methane emissions was noted, but the emissions were still lower than methane emissions from pristine mires. It is concluded that more studies are required in order to properly estimate the methane emissions from re-wetted cut-away sites. The assumption made in this study was that the methane emissions increase linearly from 0 to the original value of the pristine mire during the first 20 years of re-wetting. The assumption is mainly based on the study made by Tuittila et al (2000) which only included measurements during a three-year period but is the only information available. The assumption concerning the methane emissions at re-wetted sited is associated with a great deal of uncertainty and since the methane emissions at the re-wetted site will have a great impact on the total emissions it makes this assumption a critical one.

7.5.1.3 N_2O emissions

No data on N_2O emissions from re-wetted cut-away peatlands have been found and it was assumed that the emissions will be the same as assumed for pristine mires, 20 mg N_2O/m^2a.

7.5.2 Afforestation

7.5.2.1 CO_2 emissions/uptake

The CO_2 balance of the forest will be divided into three components:

- uptake due to net accumulation of living biomass
- accumulation of carbon in humus
- oxidation of peat

In the scenarios using afforestation as aftertreatment method it was assumed that the uptake due to forest growth and accumulation of carbon in humus would continue only during the first rotation. Thereafter the forest is mature and the balance of uptake and respiration is assumed to be equal, hence the net effect of the forest on the CO_2 balance is zero. Of course, it is very likely that the forest will be harvested and replaced by new forest. This will not lead to a continued accumulation of carbon in humus since this process also will level out. The uptake in biomass will continue if new forest is planted. However, it is then necessary to consider what happens to the harvested biomass. Will it be used as biofuel and burned? It will then lead to emissions of CO_2. Or will it be used for other purposes delaying the emissions? There are many different scenarios possible for the use of the harvested biomass and hence the climate impact of it and in this study we do not consider the further forestry regimes. The long-term effect of the afforestation will then include the avoided methane emissions of the pristine mire, the newly created carbon storage in biomass and humus and the decomposition of the remaining peat at the surrounding area and the loss of the long-term uptake of CO_2 in the pristine mire.

CO_2 uptake by biomass growth

The forest growth (uptake of CO_2 in biomass) is assumed to be the same both at the extraction area and the surrounding area. According to Hånell (1997) the forest productivity of a cut-away peatland could be estimated by the average productivity of the surrounding forests. Hånell suggests that this method is more accurate then using the available productivity schemes for drained peatlands since the soil has been significantly altered by the removal of the peat. If fertilisers (wood-ashes) are used the productivity of the cut-away peatland (both extraction area and surrounding area) should reach the average forest productivity of the region. Hånell also suggests that in some regions, where the low productivity depends mainly on the poor nutritional status, the productivity could be further increased by using fertilisers. One such area mentioned in particular is Härjedalen.

In this study the level of forest productivity was based on Hånell (1997) and the values are presented in Table 7.5.

Table 7.5. Forest productivity on cut-away peatlands based on the average productivity in the area (after Hånell, 1997).

Area	Forest Productivity	Rotation length
Småland	8.5 m^3 sk/ha a[7]	70 yr.
Bergslagen	7.5 m^3 sk/ha a	80 yr.
Härjedalen	2.5 m^3 sk/ha a	90 yr.
Coastal region of Västerbotten	3.5 m^3 sk/ha a	100 yr.

The forest productivity only comprises the stem volume production. This includes harvesting in thinnings and final cutting. The total standing biomass at thinnings and final cutting, including stem, branches, needles, stump and roots has been estimated to amount to 1.5 times the stem biomass. This assumption is the same as in many other studies, Uppenberg et al (2001), Åstrand et al (1997), Zetterberg & Klemedtsson (1996). The total uptake of CO_2 at a site with a productivity of 8.5 m^3 sk/ha a is:

$$1.5 \cdot 8.5 \cdot 420 \cdot 0.5 \cdot 0.001 \frac{m^3 sk\, kg\, kg\, C\, ton}{ha\, yr\, m^3 sk\, kg\, kg} = 2.67\, ton\, C / ha\, yr$$

420 kg/m^3 sk = dry density of stem wood.
Carbon content in stem wood = 50%.

Oxidation of peat

The decomposition of peat left after harvesting needs to be considered. At the harvested area the remaining peat-layer is shallow and in this study it was assumed that the decomposition of the remaining peat layer stays constant at the level of 1000 g CO_2 for 22 years and thereafter ceases. This is the same assumption as made in Uppenberg et al (2001) based on a remaining peat layer of 0.2 m. At the surrounding area however, decomposition will continue for a very long time. Data from a Scottish site (Hargreaves et al 2003) suggests that the oxidation of the peat layer under a forest might be lower than previously estimated. After canopy closure the decomposition rate may not be higher than 1-2 t C/ha a (which corresponds to 367-733 g CO_2/m^2a). Climatic differences both in length of vegetation period and forest productivity between Scotland and Sweden indicate that there might also be differences to the values of oxidation rate. It is likely that the rate of oxidation is lower under the Swedish conditions. In this study the lower value according to the Scottish study was therefore assumed for Swedish conditions. That value, 367 g CO_2/m^2a, is also close to the value assumed in Uppenberg et al (2001), 300 g CO_2/m^2a. We assumed the value of decomposition on the surrounding area stays constant during the first five years of afforestation and then decrease linearly to the value given by Hargreaves et al 2003 fifteen years later, and

[7] m^3 sk/ha a = Measure of forest productivity. Cubic metres of forest growth per hectare and year.

thereafter stay at that level throughout the study period or until the peat layer has been completely decomposed[8].

Accumulation in humus
There is a limit to the amount of carbon that can be added to the soil (as humus) to any site by growing trees. Sometime after the first rotation, the amount of carbon fixed by photosynthesis is balanced by the oxidation of dead organic matter and wood products, Hargreaves et al (2003), Uppenberg et al (2001). How long it will take for the soil carbon pool to reach equilibrium will depend on a number of site specific conditions. No studies on soil carbon accumulation on soils under cut away peatlands were found. In this study the same assumption as made in previous studies was used, i.e. the assumption used for uptake of CO_2 by accumulation in humus was the same as in Uppenberg et al. (2001). The assumption is that the accumulation of humic material will occur evenly distributed over the years of the first rotation. In this study the assumption corresponded to an uptake of 3.5 kg C/m^2 (70 year rotation) at the high productive sites and 2.0 kg C/m^2 (90 year rotation) at low productive sites. This corresponds to values of 183 g CO_2/m^2a and 81 g CO_2/m^2a respectively. If the soil will function as a carbon sink for a longer time period, the scenarios where afforestation was used as aftertreatment method will result in lower values of radiative forcing.

7.5.2.2 CH_4 emissions

The methane emissions at the afforested sites are in this study assumed to be ± 0. There might be a small uptake of CH_4 in forest soils during forest growth and there could be CH_4 emissions due to anoxic conditions in the remaining peat. However, both flows will be of small magnitude (Flessa (1996) and Flessa et al (1998)).

7.5.2.3 N_2O emissions

Surrounding area:
In Maljanen et al (2003) the N_2O emissions from a forest on drained peatland is estimated to 4.2 kg N_2O-N/ha a (corresponds to 660 mg N_2O/m^2 a) at a birch site. Von Arnold et al (2004c) reports a value of only 40-80mg N_2O/m^2 a (coniferous site) and 900-110mg N_2O/m^2a at deciduous forest sites depending on species. Hence there is a clear indication that the choice of tree species is important. Today, coniferous species are the most widely used in Swedish forestry. The value of nitrous oxide emissions from drained afforested peatlands used in this study was 0.08 g N_2O/m^2a, which both is within the range of the results found by von Arnold et al (2004a) & (2004c) and the value typical for forested peatlands as given by Nykänen et al (1996).

[8] We assumed that the peat layer thickness of the surrounding area is approximately half of the peat layer at the extraction area.

Extracted area.

The assumption made in this study was that the emissions decrease from 0.15 to 0.08 g N_2O/m^2a during the first five years after plantation. When the peat layer left below is assumed to have been completely decomposed (22 years after plantation, see section 7.5.2.1) the emissions were assumed to fall to 0.06 g N_2O/m^2a.

7.6 Summary of values used for simulation of radiative forcing based on peat extraction from pristine mires

Table 7.6 below summarises the scenarios based on different pristine mires and restoration methods. The first column indicates which mire type the scenario represents. The next column tells the initial emissions of methane from the pristine mire. In the third column the aftertreatment method assumed is given. In those scenarios where afforestation has been used, the value of assumed forest productivity and rotation length is also given [m^3sk/ha a]. The fourth column specifies which region the scenario is representative for. Note that the key-numbers given in this table is also used in the scenario names given in the figures presenting the results from the calculations.

Table 7.6. Summary of parameter assumptions for simulations of radiative forcing resulting from energy peat utilisation from pristine mires.

Mire	**Annual emissions in pristine state**	**Restoration**	**Comment**
Low sedge	20 g CH_4/ m^2a -62 g CO_2/m^2a	Re-wetting, -363 g CO_2/m^2 a, 20 g CH_4/ m^2a	Region 4-II & 4-I
		Afforestation, rotation 90yr., 3 m^3 sk/ha a., (346.5 g CO_2/ m^2a)	Region 4-II & 4-I
		Afforestation, rotation 90yr., 7 m^3 sk/ ha a, (808.5 g CO_2/ m^2a)	Higher productivity than average[9]
	6 g CH_4/ m^2a -62 g CO_2/m^2a	Re-wetting, -363 g CO_2/m^2 a, 6 g CH_4/ m^2a	Region 1-3
		Afforestation, rotation 90 yr., 5m^3 sk/ ha a, (577.5 g CO_2/ m^2a)	Region 2-3
		Afforestation, rotation 75 yr., 8m^3 sk/ ha a, (924 g CO_2/ m^2a)	Region 1-2
Tall sedge	23 g CH_4/ m^2a -51 g CO_2/m^2a	Re-wetting, -363 g CO_2/m^2 a, 23 g CH_4/ m^2a	Region 3-I & 4-II
		Afforestation, rotation 90 yr. 3.5 m^3 sk/ ha a, (404.3g CO_2/ m^2a)	Region 3-I & 4-II
		Afforestation, rotation 90 yr. 5.5 m^3 sk/ ha a, (635.3 g CO_2/ m^2a)	Higher productivity than average[9]
	10 g CH_4/ m^2a -51 g CO_2/m^2a	Re-wetting, -363 g CO_2/m^2 a, 10 g CH_4/ m^2a	Region 2
		Afforestation, rotation 90 yr. 5 m^3 sk/ ha a, (693 g CO_2/ m^2a)	Region 2 & 3-II
		Afforestation, rotation 75 yr. 7.5 m^3 sk/ ha a, (866.3 g CO_2/ m^2a)	Region 2
Marsh/ *Andromeda*	8 g CH_4/ m^2a -77 g CO_2/m^2a	Re-wetting, -363 g CO_2/m^2 a, 8 g CH_4/ m^2a	Region 1
		Afforestation, rotation 70 yr., 10 m^3 sk/ ha a, (1155 g CO_2/ m^2a)	Region 1
	3.5 g CH_4/ m^2a -77 g CO_2/m^2a	Re-wetting, -363 g CO_2/m^2 a, 3.5 g CH_4/ m^2a	Region 2
		Afforestation, rotation 75 yr., 8 m^3 sk/ ha a, (924 g CO_2/m^2a)	Region 2

[9] This does not directly correspond to a region, but is rather assumed as a higher productivity than average for the regions in the scenarios above. A higher productivity could both depend on the average being skewed (due to for example a high average altitude in the region, which does not represent the areas where the peatlands are located) or the use of fertilisers.

8 Agricultural peatlands

Many peatlands in Sweden have been drained in order to use the land for agricultural purposes such as growing of crops or pasture. The peatlands drained for agricultural purposes are often nutrient rich sites and strong sources of greenhouse gas emissions (Kasimir-Klemedtsson et al 2001).

8.1 Before harvesting – agricultural organic soils

Farmed organic soils are large sources of both CO_2 and N_2O emissions. When modelling the radiative forcing of the use of agricultural peatland for peat harvesting we assumed that the peatlands had been subject to drainage for a long time period. That means that the "initial" states and the drained states were the same.

8.1.1 Carbon dioxide

Extraction area: Direct measurements of the net CO_2 release from the peat in an agricultural field is complicated by the soil respiration of newly formed organic material, which is due to activity by soil organisms, roots and mycorrhizae. The following values are estimates for net CO_2 emissions from farmed organic soils in Sweden (drained peatlands) as compiled by Kasimir-Klemedtsson et al. (1997).
700-1500 g CO_2/m^2a (grassland)
2000 g CO_2/m^2a (cereals)
7000 g CO_2/m^2a (row crop, i.e. carrots, potatoes etc.)
The compilation is based on both subsidence rates, calculated oxidative loss based on climatic data and measured fluxes. In the compilation by Kasimir-Klemedtsson et al (1997) comparisons to estimates of the corresponding losses from soils in Finland and the Netherlands are made. The Finnish estimates are generally lower than the Swedish ones.

According to Kasimir-Klemedtsson et al. (2001) the CO_2 emissions from organic agricultural soils are 1000 g CO_2/m^2a. The value is given for barley, the emissions are lower for grass and higher for row crops such as carrots. 0.6-0.9 kg CO_2/m^2a will be emitted just by draining the organic soil (due to oxidation of unoxidised material i.e. peat).

According to Maljanen (2001) the emissions of CO_2 from organic agricultural soils based on measurements during both summer and winter time at a site in eastern Finland are:
Grassland: 750 g CO_2-C/m^2a (corresponds to 2750 g CO_2/m^2a).
Barley: 400 g CO_2-C/m^2a (corresponds to 1467 g CO_2/m^2a).
These values are based on measurements during one year only and were made by chamber

technique. Due to dry conditions, the grass growth may have been limited and also resulted in the high emissions from the grassland.

Lohila et al (2004a) have made eddy covariance measurements of CO_2 exchange over agricultural peat soil in southern Finland during two years. The annual net ecosystem exchange of the agricultural soil growing barley and forage grass was 771 g CO_2/m^2a and 290 g CO_2/m^2a respectively, i.e. a net loss to the atmosphere. Based on soil subsidence and chamber CO_2 flux studies, the estimates of annual net carbon loss from cultivated peat soils in the boreal zone varies form approximately 730-2550 g CO_2/m^2a (Lohila et al 2004a and references therein). The eddy covariance measurements indicates that the CO_2 losses from agricultural organic soils might be lower than estimated by Kasimir-Klemedtsson et al (1997), however that review also showed a general trend that Finnish estimates were lower.
In this study three different levels for CO_2 emissions on agricultural organic soils were made (mainly based on Kasimir-Klemedtsson et al (1997):
1100 g CO_2/m^2a (grassland)
2000 g CO_2/m^2a (cereals)
7000 g CO_2/m^2a (row crop, i.e. carrots, potatoes etc.).

Surrounding area
In this study it was assumed that the surrounding area also was agricultural organic soil but with a peat depth only 50% of the assumed depth at the extraction area. The emissions before harvesting were assumed to be the same as at the extraction area.

8.1.2 Methane

Extraction area: Farmed organic soils are negligible sources and/or sinks of CH_4, Kasimir-Klemedtsson et al. (1997) and Kasimir-Klemedtsson et al. (2001). Maljanen et al (2003) show that the agricultural used peat field is a small sink for atmospheric CH_4. However, the sink is very small (< 0.05 g CH_4/m^2a) and was ignored in this study.

Surrounding area: Also at the surrounding area the methane emissions/uptake were assumed to be negligible, i.e. ± 0.

8.1.3 Nitrous oxide

Extraction area: The N_2O emissions from farmed organic soils (drained peatlands) were according to Kasimir-Klemedtsson et al. (1997):
Grassland: 9±5 kg N_2O /ha a (corresponds to 0.9 g N_2O/m^2a, 0.4-1.4)
Cereals: 15 ± 11 kg N_2O /ha a (corresponds to 1.5 g N_2O/m^2a, 0.4-2.6)

Flessa et al (1998) have made measurements in southern Germany where the N_2O emissions were not always higher on the drained organic soils than on nearby areas.

This was probably due to the long time of drainage, the peat was decomposed to very resistant components. (The result does not apply to recently drained fen sites.) The differences in losses between different sites can be explained partly by differences in the height of the groundwater level and soil moisture content. The results from the measurements are the following values of the total annual losses of nitrous oxide:
Fertilised meadow - 4.2 kg N_2O-N/ha a (corresponds to 0.66 g N_2O /m^2a).
Fertilised field - 15.6 kg N_2O-N/ha a (corresponds to 2.45 g N_2O /m^2a).
Unfertilised meadow - 19.8 kg N_2O-N/ha a (corresponds to 3.11 g N_2O /m^2a).
Unfertilised field - 56.4 kg N_2O-N/ha a (corresponds to 8.86 g N_2O /m^2a).

In the review by Kasimir-Klemedtsson et al (2001) nitrous oxide emissions from Swedish farmed organic soils are estimated to 0.5 g N_2O /m^2a. In Maljanen et al (2003) measurements by closed chambers technique of nitrous oxide emissions from agricultural soils vary between 8.3-11.0 kg N_2O-N /ha a (1.3-1.7 g N_2O/ m^2a) depending on crops (barley, grass). The studied area in Maljanen et al (2003) had been subject to other land-use than agriculture after drainage. It had been forested for 20 years.

In another study by Maljanen et al (2004) N_2O emissions were measured at three different types of drained organic soils:

- organic agricultural soils
- abandoned uncultivated organic agricultural soils
- afforested agricultural organic soils

According to their conclusions all soils studied were sources of N_2O emissions and there was no distinct relationship between the emissions and land-use. The annual emissions varied between 2-25 kg N_2O-N/ha a (corresponding to 0.3-3.9 g N_2O/ m^2a).

In Regina et al (2004) measurements of N_2O fluxes from two agricultural peat fields, one in northern and one in southern Finland, have been made. In the north the mean annual fluxes with their standard errors during two years were:

Grass: 4 (±1.2) kg/N ha (corresponding to 0.63 g N_2O/ m^2a)
Barley: 13 (±3.0) (corresponding to 2.04 g N_2O/ m^2a)
Fallow: 4.4 (±0.8) (corresponding to 0.69 g N_2O/ m^2a)
Emissions of N_2O were larger in the south than in the north.

In the southern peat field the mean annual fluxes were:

Grass: 7.3 (±1.2) kg N_2O-N/ ha (corresponding to 1.15 g N_2O/ m^2a)
Barley: 15 (±2.6) kg N_2O-N/ ha (corresponding to 2.36 g N_2O/ m^2a)
Potato: 10 (±1.9) kg N_2O-N/ ha (corresponding to 1.57 g N_2O/ m^2a)
Fallow: 25 (± 6.9) kg N_2O-N/ ha (corresponding to 3.93 g N_2O/ m^2a)

The direct effect of adding N as a fertiliser had a minor impact on the N_2O emissions.

In this study three levels of N_2O emissions for agricultural organic soils were used:
1.0 g N_2O/ m^2a (grassland). Based on Regina et al (2004), Maljanen et al (2003) and Kasimir-Klemedtsson et al (1997).
2.5 g N_2O/ m^2a (cereals). Based on Regina et al (2004) and Kasimir-Klemedtsson et al (1997).
1.5 g N_2O/ m^2a (row-crops, i.e. carrots, potatoes etc.). Based on Regina et al (2004).

Surrounding area: The same assumption of N_2O emissions levels as for the extraction area was used.

8.2 Drained agricultural soil, before harvesting

In this study we assumed that the emissions from the agricultural field stay at the same level during the drainage period. It could be argued that the emissions would be similar to emissions from an agricultural field in fallow, but it could also be argued that there is no need (or a smaller need) for a drainage period since the cultivated peat is already drained. Assuming the emissions to be the same as at the field will give ± 0 in radiative forcing during the period of drainage before harvesting.

8.3 During harvesting

No studies on greenhouse gas emissions from agricultural peatland under harvesting have been found. It is not likely that the same values as for pristine mires under harvesting is valid. This since the high activity of the cultivated soil may not cease after the cultivation has ceased.

8.3.1 Carbon dioxide

Extraction area: In this study the assumption that the high CO_2 emissions from the agricultural peat field will stay constant during the entire harvesting period was made.

Surrounding area: The CO_2 emissions are assumed to stay high during the first five years and then linearly decrease due to the growth of forest and other vegetation year 5-20 of the harvesting period, reaching half of the initial emissions by the end of the harvesting period.

8.3.2 Methane

Extraction area: The methane emissions will probably be negligible during harvesting, this since the drainage enhances the possibilities for oxidation of formed methane before reaching the atmosphere. However, as in the case of natural mires that are drained and subject to peat harvesting, it is probably important to keep the ditches clear from vegetation in order to avoid large methane emissions.

Surrounding area: The same assumption concerning the methane emissions from the surrounding area as for the emissions from the extraction area was made.

8.3.3 Nitrous oxide

No studies on how the emissions of nitrous oxide from former agricultural peat soils change during the harvesting period compared to the former activity were found. However, the microbial/biological activity in the agricultural soil has proven to stay high even after cultivation has ceased (Maljanen et al 2004). During harvesting the compaction and working of the soil will stay high at least at the extraction area. In this study it was assumed that the N_2O emissions remain at the high initial value during harvesting, both on the extraction area and on the surrounding area.

8.4 After-treatment

To estimate the greenhouse gas emissions from a cut-away agricultural peatland is difficult according to L., Klemedtsson (2004, personal communication). The biological activity is much higher in former agricultural soils than in other peat soils.

8.4.1 Restoration of wetland

No studies on greenhouse gas emission fluxes from agricultural peatlands restored to wetlands were found. It is reasonable to assume that the cut-away site will resemble a pristine cut-away site since most of the peat has been removed. The conditions might be different at the surrounding area where a considerable peat depth still is present. However, due to lack of data, no distinguished differences in the greenhouse gas balances from the restored extraction area and surrounding area were made.

8.4.1.1 CO_2 emissions

The same assumption as for restored cut-away sites that originally were pristine mires was made, see section 7.5.1.

8.4.1.2 CH_4 emissions

In Flessa et al (1996) the annual CH_4-C emission observed when re-wetting a long-term drained organic soil, was very small, 36 g /ha a (corresponds to 4.8 mg CH_4/m^2) because the organic carbon was so unreactive (Flessa et al 1998). Again the CH_4 production is more related to the production of fresh organic litter and it will probably take a few years before the methane production will rise and resemble that of a pristine peatland (compare to section 7.5.1). In our study the same assumption as for restored cut-away pristine mires is made both for the extraction area and the surrounding area.

8.4.1.3 N_2O emissions

No data on N_2O emissions from re-wetted cut-away peatlands originally used for agriculture have been found and it is assumed that the emissions are the same as for pristine mires (20 mg N_2O /m^2a).

8.4.2 Afforestation

8.4.2.1 Carbon dioxide emissions / uptake

Lohila et al (2004b) have made measurements on CO_2 losses on afforested agricultural peat soil. The measured forest was a 35 year-old pine stand and the relatively high carbon losses from the cultivated peat soils are reduced by means of afforestation. At the investigated site, the peat layer had not been removed, hence it might not be directly comparable to a afforested cut-away site but rather to the surrounding area. In the same study, measurements were also made at a mineral soil forest, which could be said to more resemble an extracted area. The difference in the annual balances between the afforested peat field and the mineral soil forest was great, the mineral soil site showing considerable carbon uptake during the course of the year.

Oxidation of peat
According to Aro et al (2004) the instantaneous soil respiration rates [g CO_2/m^2h] in afforested cut-away peatland were lower then in afforested peat fields or in drained peatland forests. The higher humification and higher content of recalcitrant compounds in the cutaway peatland may cause this.

Extraction area: The decomposition of remaining peat at the cut-away site was assumed to be small and cease after a couple of years when the remnant peat is completely decomposed. For sites with a slower rate of decomposition (1100 g CO_2/m^2a) it is assumed that the emissions stay constant until 20 years after the afforestation when the remaining peat layer is completely decomposed, see section 7.5.2.1. For sites with a higher rate of decomposition it is assumed that the decomposition rate stays constant during the first five years of afforestation and then decreases linearly and ceases after 20 years. In the scenarios with very high rate of decomposition the decomposition will cease already after 8 years.

Surrounding area: In this study we have assumed a higher rate of CO_2 emissions from the surrounding area, i.e. a higher rate of decomposition, since there is assumed to still be a considerable layer of peat after afforestation. We also assume a higher decomposition rate in the former agricultural peat soil than in afforested sites that were former natural peatlands. The assumption is that the decomposition stays constant during the first five years after afforestation and then decreases to a level of 733 g CO_2/ m^2a (corresponds to the higher value given by Hargreaves et al 2003). The decomposition ceases when the peat layer is completely decomposed. In the scenarios with the highest rate of decomposition there will be a decrease to half the initial value after five years.

CO_2 uptake by biomass growth & CO_2-C accumulation in humus
The same assumptions concerning the CO_2 uptake by biomass growth and CO_2-C accumulation in humus were used for these sites as for cut-away afforested sites that originally were pristine mires. The assumed forest productivities used for the different scenarios are indicated in Table 8.1.

8.4.2.2 Methane emissions

The same assumption as for afforested cutaway pristine mires (section 7.5.2.2) is used. The methane emissions were assumed to ± 0 for both the extraction area and the surrounding area. Maljanen et al (2003) show that the organic peat field is a smaller sink for atmospheric CH_4 than the afforested site. However both sinks are small (< 0.05 g CH_4/m^2a) and were ignored in this study.

8.4.2.3 Nitrous oxide emissions

The few studies that exist on N_2O emissions from afforested agricultural peatlands indicate that afforestation might not decrease N_2O emissions from the forest floor. Pihlatie et al (2004) have measured N_2O emissions with enclosure and eddy covariance techniques from an afforested peat field in western Finland. The measurements show that the fluxes were of the same order as those measured from organic agricultural soils and considerably higher than those measured from mineral soil forests. Maljanen et al (2004) have measured the N_2O fluxes from organic agricultural soils (growing grass or barley, 2 sites), abandoned uncultivated organic agricultural soils (5 sites) and afforested agricultural organic soils (6 sites). All soils studied were sources of N_2O emissions and there was no distinct relationship between the emissions and land-use. The annual emissions varied between 0.3-3.9 g N_2O/m^2a. The study showed that some afforested organic soils emitted N_2O at higher rate than cultivated organic soils, even 30 years after the afforestation.

In this study we therefor distinguished between the cutaway site i.e. the extraction area and the surrounding area. The emissions were set to significantly higher values at the surrounding area than at the cut- away site.

Extraction area: The N_2O emissions were assumed decrease to 10% of the initial emissions during the first five years of afforestation and then slow down the rate of decrease and reach the value of forests of 0.06 g N_2O/m^2a after 20 years. Thereafter the value was assumed to stay constant throughout the study period.

Surrounding area: The N_2O emissions were assumed to decrease from the initially high value to 80% after 20 years and thereafter stay constant at that level until the remaining peat layer has been decomposed completely and the emissions will then reach 0.06 g N_2O/m^2a.

8.5 Summary of parameter assumptions for simulations of radiative forcing from using peat from agricultural peat fields for energy production

In Table 8.1 a description of the different scenarios made for peat extraction from agricultural peatlands is given. The denotation is similar to the denotation in Table 7.6. The methane emissions from the agricultural fields before the peat harvesting are assumed to be zero for all scenarios. Also the methane emissions form the afforested areas are assumed to be zero in all scenarios.

Table 8.1. Summary of parameter assumptions for the simulations of radiative forcing resulting from energy peat utilisation from agricultural peat fields.

Mire	**Emissions before harvesting**		**Restoration**	**Comment**
	CO_2 emissions	N_2O emissions		
Grass	1100 g CO_2/m^2 a	1.0 g N_2O/m^2 a	Re-wetting, CH_4 = 10 g CH_4/m^2a, CO_2 = -363 g CO_2/m^2a	All regions
			Afforestation, rotation = 100 yr., 3.5 m^3 sk/ha a, 404.3 g CO_2/m^2 a	Region 4-II
			Afforestation, rotation = 90 yr., 2.5 m^3 sk/ha a, 288.8 g CO_2/m^2 a	Region 3
			Afforestation, rotation = 80 yr., 7.5 m^3 sk/ha a, 866.3 g CO_2/m^2 a	Region 2
			Afforestation, rotation 70 yr., 10 m^3 sk/ha a, 1155 g CO_2/m^2 a	Region 1 (IV)
Barley	2000 g CO_2/m^2 a	2.5 g N_2O/m^2 a	Re-wetting, 10 g CH_4/m^2 a, CO_2 = -363 g CO_2/m^2a	All regions
			Afforestation, rotation = 100 yr., 3.5 m^3 sk/ha a, 404.3 g CO_2/m^2 a	Region 4-II
			Afforestation, rotation = 90 yr., 2.5 m^3 sk/ha a, 288.8 g CO_2/m^2 a	Region 3
			Afforestation, rotation = 80 yr., 7.5 m^3 sk/ha a, 866.3 g CO_2/m^2 a	Region 2
			Afforestation, rotation 70 yr., 10 m^3 sk/ha a, 1155 g CO_2/m^2 a	Region 1 (IV)
Row-crops (potatoes, carrots etc.)	7000 g CO_2/m^2 a	1.5 g N_2O/m^2 a	Re-wetting, 10 g CH_4/m^2 a, CO_2 = -363 g CO_2/m^2a	All regions
			Afforestation, rotation = 100 yr., 3.5 m^3 sk/ha a, 404.3 g CO_2/m^2 a	Region 4-II
			Afforestation, rotation = 90 yr., 2.5 m^3 sk/ha a, 288.8 g CO_2/m^2 a	Region 3
			Afforestation, rotation = 80 yr., 7.5 m^3 sk/ha a, 866.3 g CO_2/m^2 a	Region 2
			Afforestation, rotation 70 yr., 10 m^3 sk/ha a, 1155 g CO_2/m^2 a	Region 1 (IV)

9 Drained forested peatlands – low productivity

This section concerns the climate impact from energy peat production from peatlands that have been drained for forestry and has a low productivity (defined as 1-4 m^3/ha a). Based on data from the Swedish National Forest Inventory 1998 – 2002 the estimated occurrence of such peatlands is 239 * 10^3 ha (von Arnold 2004). In Hånell (1988) estimates of the forest productivity on drained peatlands in different climatic regions are presented. Table 9.1 shows what peatlands at what sites that according to Hånell (1988) will have a post-drainage productivity ≤ 4.0 m^3/ha a.

Table 9.1 Peatlands with post-drainage forest productivity ≤ 4.0 m^3/ha a.

Mire type	Annual air temperature sum[10]
Tall herb type / Aconitum-Filipendula	≤ 600°
Low herb type/ Maianthemum-Viola	≤ 700°
Bilberry horsetail type / Vaccinium myrtillus	≤ 700°
Tall sedge type / Carex rostrata	≤ 1000°
Dwarf shrub type / Ledum Palustre	≤ 1100°
Carex Globularis type	all sites
Low sedge type / Eriphorum vaginatum	all sites
Marsh andromeda – cranberry type	all sites

It is noteworthy that sites where drainage has been performed but is not properly maintained, the productivity could be low although the climatic factors indicates a higher productivity potential.

9.1 Before harvesting – forested site

Drained peatlands used for forestry are assumed to be net sources of greenhouse gases (Olsson et al 2002). The reason is said to be the rapid decomposition of the accumulated peat layer due to the enhanced accessibility of oxygen. In Klemedtsson et al (2002) an attempt to make estimates of the greenhouse gas fluxes from drained forests in Sweden is made. However, it is concluded that data on CO_2 (and N_2O) net fluxes from drained forests are very uncertain and further research is needed. Measurements made by von Arnold (2004) and Minkkinen et al (2002) show that there might be sites of afforested drained peatlands that are sinks of greenhouse gases. Von Arnold (2004) distinguishes between poorly and well drained sites and concludes that it is more probable that poorly drained sites are net sinks of greenhouse gases while well drained sites might be net

[10] Based on days with an air temperature > +5 °C.

sources. Minkkinen et al (2002) show that there is a considerable difference of net greenhouse gas balances of drained forest sites depending on trophy.

9.1.1 Carbon dioxide

Minkkinen et al (2002) concludes that in Finland the storage of carbon and the rate of carbon accumulation in peatlands have been reported to either increase or decrease after drainage, depending on trophy and climatic conditions. Measurements made by von Arnold et al (2004a) and (2004c) of the mean annual dark soil CO_2 release of drained and undrained peatlands in southern Sweden showed that the emissions were significantly higher at the drained sites than at the undrained sites. The dark soil[11] CO_2 emissions from the coniferous sites were estimated to 0.9-1.9 kg CO_2/m^2a and from the deciduous sites 1.4 -2.3 kg $CO_2/\ m^2a$. The dark soil CO_2 release is composed by both the amount of CO_2 resulting from the oxidation of the remaining peat layer but also the respiration by plant roots. Von Arnold et al (2004a) and (2004c) also estimates the uptake of CO_2 by the growing forest and other biomass and the net balances of CO_2 fluxes from the ecosystems are estimated. The estimates of the net CO_2 balance show that all drained sites are sinks of CO_2 and the strength of the sink depends on the productivity of the site. In von Arnold et al (2004b), which is based on von Arnold et al (2004a) and (2004c), it is concluded that drained peatlands on shallow peat layers can be large sinks of greenhouse gases. The total balance is strongly dependent on the productivity of the site, a higher productivity will result in a larger sink. The results from von Arnold et al (2004b) also shows that coniferous sites generally are larger sinks than deciduous sites due to the larger binding of C in the coniferous species. The oxidation rate of the under-laying peat layer was similar at both deciduous and coniferous sites.

Micrometeorological measurements (i.e. both photosynthesis and respiration are encountered) performed during 6 years at Norunda showed a variation of the net annual flux of C between –6.6 and +109 g C/m^2 (positive value means net emissions from forest ecosystem to atmosphere). Only one of the six years showed a net annual flux corresponding to a net sink , i.e. negative value (Klemedtsson et al 2002 & Lindroth et al. 1998).

Olsson et al. (2002) conclude that the net CO_2 emissions from forests on drained peatland lie somewhere between 50-100 g C/m^2 (in the lower range for nutrient poor sites and in the higher range for nutrient rich sites), mainly based on measurements of soil subsidence.

[11] Dark soil CO_2 emissions are measured by dark chambers. By not letting any light into the chamber the respiration of the ground flora will be prohibited.

The conclusion we draw from the different studies is that whether a drained and forested peat soil is a net sink or source depends on both the degree of drainage, peat nutrient level and the productivity (which is dependent both on peat nutrient content and climatic conditions). However, we have limited information on peat nutrient level of the drained forest sites used for energy peat production. In this study different levels of productivity were assumed, but the main focus was on low-productivity sites and the assumed levels were therefore in the lower range of productivity. Assumptions on oxidation rates and sequestration of carbon in biomass were also made. The estimates of oxidation rates were based on von Arnold et al (2004a) and (2004c). However, the measurements by von Arnold are made in the southern parts of Sweden and the results might not be relevant for other regions in Sweden due to differences in climatic conditions. Von Arnold et al (2004a) and (2004c) have also made estimates of the CO_2 NEE (net ecosystem exchange) from the studied sites. The overall conclusion is that the drained sites are net sinks of CO_2. The values used by von Arnold et al (2004b) to estimate the uptake of CO_2 in biomass are quite high; 1.4 kg CO_2/m^2corresponds to a forest productivity of 10-11 m^3 sk/ha a.

In this study we assumed oxidation rates similar to those measured by von Arnold et al (2004a) & (2004c) and based our estimates of carbon uptake on more moderate forest productivities. The assumption of lower forest productivities results in the ecosystems being net sources of CO_2 as measured by Lindroth et al (1998). A number of scenarios based on these assumptions were made and are presented in Table 9.2. We also made one scenario where the drained forest was a net sink of CO_2 before the start of peat harvesting. In that scenario the values given in von Arnold et al (2004c) for a low productivity pine site was used.

9.1.2 Methane

In Martikainen et al (1995) it was concluded that the reduction of methane emissions due to drainage is dependent on how much the water table is lowered and a site can actually become a net sink of atmospheric methane after drainage. The flux of atmospheric methane from forests on drained peatlands have both been measured to be positive and negative (i.e. the forests could either be sources or sinks for atmospheric methane). According to von Arnold et al. (2004a) and (2004c) the methane emissions from drained forests on organic soils were much lower, 10 times lower, on deciduous sites and even zero at coniferous sites compared to undrained mires. The absolute values in von Arnold et al. (2004a) and (2004c) lie within the range of 0 -1.6 g CH_4/ m^2a and 0.4 – 1.3 g CH_4/m^2a for the coniferous and deciduous sites respectively. In our study it was assumed that the methane emissions/uptake from the already drained area is negligible, i.e. 0.

9.1.3 Nitrous oxide

In Maljanen et al (2003) the emissions of nitrous oxide from forested peatlands is estimated to 4.2 kg N_2O-N/ha a (corresponds to 0.66 g N_2O/ m^2a). In Uppenberg et al (2001) the N_2O emissions from the afforested surrounding area of the harvesting site are based on Klemedtsson (personal communication) and set to 0.14 –0.7 g N_2O/m^2a (best estimate 0.42 g N_2O/m^2a). According to Martikainen et al (1995) only nutrient rich sites have a large increase in N_2O emissions due to drainage. According to von Arnold et al (2004a) and (2004c) the N_2O emissions were higher at the drained forest sites than at the undrained mire sites. However those studies also showed that the trophy of the site and the tree species could affect N_2O emissions. The emissions of N_2O according to von Arnold et al. (2004a) and (2004c) were 40-80 mg N_2O/m^2a and 90-1250 mg N_2O/m^2a for the coniferous and deciduous sites respectively. The highest values were recorded for the nutrient rich deciduous site (alder site).

In our study differentiated assumptions were made concerning the N_2O emissions of different sites of drained forest. Coniferous sites were assumed to have N_2O emissions of 0.08 g N_2O/m^2a (same assumption as for afforested sites, see section 7.5.2.3. For deciduous sites two levels were used in the simulations, 0.2 g N_2O/m^2a at less active sites and 0.9 g N_2O/m^2a at sites of high activity (high rate of oxidation).

9.2 Before harvesting – clear cut and supplementary drained

9.2.1 Carbon dioxide

The peatlands represented in this chapter have been under drainage for a period before the start of harvesting. Some of the more easily decomposed peat might already have been decomposed. This means that the decomposition of the peat layer might be slower than at a newly drained site (Olsson et al. 2002). The CO_2 emissions will probably be similar (or smaller) than the emissions from pristine peatlands subject to peat harvesting. Even if the sites already are subject to drainage it might be necessary to drain the area more effectively before starting the peat harvesting. It is also assumed that the harvesting area will be clear-cut before starting. In this study it is assumed that the CO_2 emissions from the clear-cut sites are approximately the same as for the pristine mire in the same state (i.e. drained and under harvesting). The assumption is that the CO_2 emissions during the period of pre-harvesting drainage are approximately 1000 g CO_2/m^2a. In case the oxidation was significantly lower than 1000 g CO_2/m^2a a linear increase has been assumed where the oxidation reaches 1000 g CO_2/m^2a three years after the start of drainage. In those cases where the rate of oxidation already is higher (than 1000 g CO_2/m^2a) it is assumed that the oxidation rate will stay constant at that higher rate during the pre-harvesting period.

9.2.2 Methane

In this study methane emissions were assumed to stay at negligible levels during the harvesting period, at both the extraction area and at the surrounding area.

9.2.3 Nitrous oxide

In this study the N_2O emissions both at the extraction area and the surrounding area were assumed to stay constant during the drainage period. The emissions from the coniferous sites, where N_2O emissions are rather small, are similar to those of pristine peatlands under drainage (0.15 g N_2O/m^2a). For the deciduous sites with initially higher N_2O emissions (> 0.15 g N_2O/m^2a) the emissions were assumed to stay at that high level during the pre-harvesting period.

9.3 During harvesting

9.3.1 Carbon dioxide

For the coniferous sites we assumed the same as for the pristine mires in the same stage (during harvesting). The emissions were assumed to stay constant at the extraction area but decrease somewhat in the surrounding area due to less working of the ground and in order to compensate for the uptake in biomass that also occur at the surrounding area. At the deciduous sites where the rate of decomposition in some cases were assumed to be significantly higher we also assume a higher level of CO_2 emissions during harvesting. (At the sites with initially very high rates of decomposition, the CO_2 emissions were assumed to decrease to 50% of the initial value by the end of the harvesting period.)

9.3.2 Methane

In this study the methane emissions from the site (extraction and surrounding area) during harvesting were considered negligible. There might still be some emissions from the ditches but they could be kept low by keeping the ditches free from vegetation.

9.3.3 Nitrous oxide

The same assumption as for originally pristine mires during harvesting was made, see section 7.3.3. On the extraction area the emissions of nitrous oxide are assumed to decrease as the harvesting goes on but will increase again at the end of the harvesting period. This assumption was made for scenarios with initial N_2O emissions of 0.08 and 0.2 g N_2O/m^2a At the surrounding area the emissions are reduced to 0.08 g N_2O/m^2a after five years of harvesting and then stay at that level. At the site with the initial emission level of 0.9 g N_2O/m^2a the emissions decreases both at the extraction area and at the surrounding area to 0.5 g N_2O/m^2a after ten years and five years of harvesting respectively. The emissions then remain at this level at both the extraction and the surrounding area.

9.4 After-treatment

9.4.1 Restoration of wetland

The assumptions made in this study concerning the emissions/ uptake of greenhouse gases from the re-wetted sites of cut-away peatlands that were drained and forested before the peat harvesting were the same as for the originally pristine peatlands in the same state, see section 7.5.1.

9.4.1.1 CO_2 emissions

In this study is was assumed that the CO_2 uptake will increase linearly during the first five years after restoration to 363 g CO_2/m^2a (Tuittila et al 1999) and thereafter stay constant throughout the study period, see section 7.5.1.

9.4.1.2 CH_4 emissions

The CH_4 emissions of the newly created wetland were assumed to rise from 0 to 10g CH_4/m^2a during a twenty-year period after the rewetting event. The reason for choosing this value was that this is in the middle of the range of what was assumed for different types of pristine mires that are extracted and then re-wetted. Since we have no information on what types of mires the drained forests were before the drainage, more specific assumptions were difficult to make.

9.4.1.3 N_2O emissions

The N_2O emissions were assumed to be small, and stay constant at a level of 20 mg N_2O/m^2a, see section 7.5.1.

9.4.2 Afforestation

9.4.2.1 CO_2 emissions

CO_2 uptake by biomass growth

The scenarios made in this study assume that the forest productivity of the afforested area will be higher than the forest productivity before the peat harvesting. We assumed different productivity ranging between 4.5 – 10 m^3 sk/ha a.

CO_2-C accumulation in humus
The accumulation of carbon in the ground was assumed to different levels depending on forest productivity. The same two levels as for afforested pristine mires were assumed (i.e. ~20g C/m^{2}a for low productivity sites and ~50 g C/ m^{2}a for high productivity sites), see section 7.5.2.1.

Oxidation of peat
The same assumptions of the oxidation rate as for pristine mires in this state was used, i.e. the decomposition at the extraction area is 1000 g CO_2/m^{2}a for approximately 22 years after the afforestation and then ceases. At the surrounding area the emissions stay constant during the first five years of afforestation and then decrease linearly to a value of 367 g CO_2/m^{2}a after 15 years and stay constant at this level until the end of the study period (or until the peat layer has oxidised completely).
At sites where the rate of decomposition was assumed to be significantly higher than 1000 g CO_2/m^{2}a a linear decrease at the extraction area during the 22 years of residual oxidation was assumed.

9.4.2.2 CH_4 emissions

Methane emissions were assumed to be negligible at the afforested site, both on the extraction area and surrounding area, see section 7.5.2.2.

9.4.2.3 N_2O emissions

At sites with initially low emissions of N_2O it was assumed that the N_2O emissions at the extracted area after afforestation are similar to the values measured by von Arnold et al (2004c), i.e. 0.06 g N_2O/m^{2}a. The emissions were assumed to decrease from 0.2 to 0.08 g N_2O/m^{2}a during the first five years after harvesting. After 20 years (and for the rest of the simulation period) the emissions were assumed to be 0.06g N_2O/m^{2}a.

A somewhat higher value was used for the surrounding area, i.e. 0.08 g N_2O/m^{2}a. For the sites with initially high N_2O emissions (0.9 g N_2O/m^{2}a) it was assumed that the emissions at the surrounding area stay at a higher level. The emissions decrease from 0.5 to 0.2 g N_2O/m^{2}a during 20 years after afforestation and then stay constant at that level.

9.5 Summary of parameter assumptions for simulations of radiative forcing from energy peat utilisation from drained forested peatlands

In Table 9.1 a description of the different scenarios made for peatlands drained for forestry is given. The first column tells for what type of forest (coniferous or deciduous) the assumed values of the different parameters are valid. The next three columns give the annual net emissions/uptake of CO_2, CH_4 and N_2O from the drained forest before the start of harvesting (and before the possibly necessary additional drainage that will have to be done before the start of harvesting). In the column for CO_2, values of both the assumed rate of peat oxidation and the forest productivity are given. There are two exceptions for the scenarios where the drained forests were assumed to be net sinks of CO_2 and where only the value of net ecosystem exchange is given (NEE). The last column in the table will give the combination of those two values, i.e. the net emission/uptake of the peatland –forest system. A negative value indicates net uptake from the atmosphere and a positive value indicates net emissions to the atmosphere.

The fifth column (restoration) tells what aftertreatment method that has been assumed for that specific scenario and the values of some parameters of that methodology. For re-wetting the value of the long-term methane emissions is given and for afforestation the forest productivity and the rotation period is given. In Uppenberg et al (2001) 3 m^3/ha a has been assumed as a worst case for low productivity. In this study both 2 and 3 m^3sk/ha were used in the different scenarios as a value of low productivity sites before peat harvesting, whereas 4.5 and 5.5 m^3sk/ha a were low values for the forest productivity after peat harvesting.

Table 9.2. Summary of parameter assumptions for simulations of radiative forcing resulting from energy peat utilisation from drained forested peatlands.

Forest type	**Annual emissions before harvesting [g gas/m²a]**			**Restoration**	**Net C emission/ uptake before harvesting**
	CO_2	CH_4	N_2O		
Coniferous	Ox. 900 g CO_2/m^2 Prod. 3.0 m^3 sk/ha a	0	0.08	Re-wetting, 10 g CH_4/m^2a –363 g CO_2/m^2a	151 g C/m^2a
	Ox: 900 g CO_2/m^2 Prod: 3.0 m^3 sk/ha a	0	0.08	Afforestation, rotation = 80 yr., 7.5 m^3 sk/ha a, 866.3 g CO_2/m^2a	151 g C/m^2a
	Ox:1900 g CO_2/m^2 Prod: 3.0 m^3 sk/ha a	0	0.08	Re-wetting, 10 g CH_4/m^2a –363 g CO_2/m^2a	455 g C/ m^2a
	Ox: 1900 g CO_2/m^2 Prod: 3.0 m^3 sk/ha a	0	0.08	Afforestation, rotation 70 yr., 10 m^3 sk/ha a, 1155 g CO_2/m^2a	455 g C/ m^2a
	Ox: 450 g CO_2/m^2 Prod: 3.0 m^3 sk/ha a	0	0.08	Re-wetting, 10 g CH_4/m^2a, –363 g CO_2/m^2a	Region 3 & 4 ; 28g C/ m^2a
	Ox: 450 g CO_2/m^2 Prod: 3.0 m^3 sk/ha a	0	0.08	Afforestation, rotation = 100 yr., 5.5 m^3 sk/ ha a, 635.3 g CO_2/m^2a	28g C/ m^2a
	Ox: 450 g CO_2/m^2 Prod:2.0 m^3 sk/ha a	0	0.08	Afforestation, rotation = 90 yr., 4.5 m^3 sk/ha a, 519.8 g CO_2/m^2a	59 g C/ m^2a
	Low productive pine NEE : 200 g CO_2/m^2	0	0.08	Re-wetting, 10 g CH_4/m^2a, CO_2 = -363 g CO_2/m^2a	According to von Arnold et al (2004c). –54 g C/m^2a
	Low productive pine NEE : 200 g CO_2/m^2	0	0.08	Afforestation rotation = 70 yr., 8 m^3sk/ha a, 924 g CO_2/m^2a	
Deciduous	Ox: 1400 g CO_2/m^2 Prod: 3.0 m^3 sk/ha a	0	0.2	Re-wetting, 10 g CH_4/m^2a, CO_2 = -363 g CO_2/m^2a	287g C/ m^2a
	Ox: 1400 g CO_2/m^2 Prod: 3.0 m^3 sk/ha a	0	0.2	Afforestation, rotation = 80 yr., 7.5 m^3 sk/ha a, 866.3 g CO_2/m^2a	Region 2; 287g C/ m^2a
	Ox: 2300 g CO_2/m^2 Prod: 3.0 m^3 sk/ha a	0	0.9	Re-wetting, 10 g CH_4/m^2a, CO_2 = -363 g CO_2/m^2a	532 g C/m^2a
	Ox: 2300 g CO_2/m^2 Prod: 3.0 m^3 sk/ha a	0	0.9	Afforestation, rotation = 70 yr., 10 m^3 sk/ha a, 1155 g CO_2/m^2a	Region 1-V; 532 g C/m^2a
	Ox: 700 g CO_2/m^2 Prod 3.0 m^3 sk/ha a	0	0.2	Re-wetting, 10 g CH_4/m^2a, CO_2 = -363 g CO_2/m^2a	96 g C/m^2a
	Ox: 700 g CO_2/m^2 Prod:3.0 m^3 sk/ha a	0	0.2	Afforestation, rotation = 100 yr., 5.5 m^3 sk/ha a, 635.5 g CO_2/m^2a	Region 4 & 3 96 g C/m^2a
	Ox: 700 g CO_2/m^2 Prod: 2.0 m^3 sk/ha a	0	0.2	Afforestation, rotation = 90 yr., 4.5 m^3 sk/ha a, 519.8 g CO_2/m^2a	Region 4 & 3 127g C/ m^2a

10 Old peat harvesting sites

Old peat harvesting areas refers to areas that earlier have been used for peat harvesting but has not been completed or after-treated. It could be areas used for harvesting of peat litter for livestock rearing or energy peat harvesting areas.

10.1 Before harvesting

No studies on greenhouse gas balances from old peat harvesting areas have been found. According to L-E Larsson (personal communication, 2004) there are two main types of peatlands historically used for peat harvesting. At some areas energy peat was extracted from the circumference mire. In those cases there has been quite a severe impact on the entire peatland and the vegetation has changed to increased occurrence of dwarf-shrubs like *Vaccinum uliginosum, Calluna vulgaris* etc. At the other category of harvested peatlands, peat litter for livestock rearing was extracted. Only the upper layer of low humified peat was harvested and these sites are probably often suitable for energy peat harvesting. Usually the drainage was done by simply using twigs, i.e. no drainage ditches were dig but the in flow of water was limited, and the drainage could easily be put out of the running (by removing the twigs). Many of these sites have therefore been re-wetted (personal communication L-E, Larsson, 2004) and have been returned to carbon accumulating peatlands again. However, at some of these sites the drainage ditches are still more or less effective and there might be a thicker layer of aerated peat then what is normal at a pristine peatland.

Three kinds of old harvested peatlands were distinguished, however they were all assumed to have been of the raised bog type in the pristine state:

- Peatlands where energy peat has been harvested. The harvesting and drainage has drastically altered the vegetation of the peatland.
- Peatlands where peat litter for livestock rearing has been harvested and where the drainage have been put out of the running.
- Peatlands where peat litter for livestock rearing has been harvested and where the drainage has been partly effective for a long time after the harvesting.

For all old harvesting areas we considered that the new harvesting areas will cover not only the old extraction area but also pristine mire and areas only affected by drainage We assumed that 20% of the area actually had been subject to former harvesting. The rest of the area has not been harvested but affected by the drainage. The historic harvesting was not complete, i.e. there is a considerable peat layer left on the already harvested sites that could be extracted. In fact it was assumed that the amount of peat extracted per m^2 at these areas was the same as at the other peatland types in this study.

10.1.1 Carbon dioxide

According to Tuittila et al (1999), the carbon balance at a re-wetted peat harvesting area becomes positive (system accumulating carbon) only a few years after rewetting. This is true for sites that are more or less continuously submerged. At drier sites the carbon balance was still negative after the three years of study.

Drainage ditches will not be effective forever. Both due to plant growth (a thick plant cover will deteriorate the function of the ditches) and the subsidence of ground level due to oxidation of the aerated peat layer, the ditches will become less effective with time. It is assumed that after a few decades the ditches have little function unless maintenance is conducted.

In this study simulations were made both for sites assumed to have become re-wetted (drainage ditches put out of running) and for sites where the drainage ditches still have some function. At sites that have been re-wetted it was assumed that the carbon accumulation has increased. This since the harvested areas have a higher production of plant material and hence higher accumulation rate of CO_2. It was assumed that the carbon accumulation rate has doubled due to more nutrient rich conditions at the newly re-wetted site. At sites where drainage ditches still are effective it was assumed that, the CO_2 uptake has turned into net emissions. The drainage has been assumed to be somewhat less effective than the drainage at active peat harvesting areas. A CO_2 oxidation rate of half the value assumed for harvesting drained peatlands was used. The surrounding area (not the open pits) was assumed to have a net CO_2 balance of $\pm$ 0.

10.1.2 Methane

The emissions of CH_4 will be dependent on the production of new plant material. In this study it was assumed that the methane emissions from these sites are relatively high. Methane emissions from old harvesting sites can be compared to emissions from ditches and measurements in drainage ditches have shown to be very high (Sundh et al 2000). The value of methane emissions from the harvested area at sites where rewetting have occurred was assumed the same as the 90:e percentile for tall sedge or low sedge mires, depending on original mire type, as determined by Nilsson et al (2001).

For areas where rewetting not has occurred, it was assumed that the methane emissions have ceased at the harvested areas and is of original magnitude at the non-harvested areas.

10.1.3 Nitrous oxide

The N_2O emissions were assumed to be small and of the same order as for pristine mires. A value of 20mg N_2O/m^2a was used.

10.2 Drained - before harvesting

The old peat harvesting areas need to be newly drained, just like a pristine mire site.

10.2.1 Carbon dioxide

In this study it was assumed that the emissions of CO_2 increase substantially during the drainage period just as for pristine mires, see section 7.2.1. The assumption was that the CO_2 emissions rise to 1000 g CO_2/m^2a both at the extraction area and at the surrounding area. The increase is linear and will reach 1000 g CO_2/m^2a three years after the new drainage has been performed. This assumption was made both for the extraction area and the surrounding area.

10.2.2 Methane

The same assumption as for pristine mires was made. That means that the methane emissions decrease to 10% of the original emissions at the extraction area, but not below 1.5 g CH_4/m^2a, and to 25% at the surrounding area, but not below 3 g CH_4/m^2a.

10.2.3 Nitrous oxide

The same assumption as for drained pristine mires was used, the emissions of nitrous oxide during the pre-harvesting drainage period are 0.15 g N_2O/m^2a, both at the extraction area and at the surrounding area.

10.3 During harvesting

Many of the assumptions made for this type of peatlands under harvesting were the same as made for pristine mires in this stage, see section 7.3.

10.3.1 Carbon dioxide

The rate of oxidation was assumed stay high at the extraction area (1000 g CO_2/m^2a) but will decline linearly at the surrounding area to 300 g CO_2/m^2a by the end of the harvesting period.

10.3.2 Methane

The emissions at the extraction area stay constant during the harvesting period and the emissions from the surrounding area decrease and reach 0 by the third year of harvesting.

10.3.3 Nitrous oxide

The emissions from the extraction area were assumed to have a cyclic development during the harvesting period. They decrease during the first years and then increase again towards the end of the harvesting period. The assumption is the same as for pristine mires. The emissions of nitrous oxide from the surrounding area were assumed to decrease during the first five years of harvesting and then stay at a level of 0.08g N_2O/m^2a.

10.4 Aftertreatment

Also for this stage it was assumed that the mires previously used for peat harvesting will have emissions during the aftertreatment period similar to pristine mires in the same stage.

10.4.1 Restoration of wetland

The assumptions made concerning the CO_2 and N_2O emissions from a restored wetland are the same as for pristine mires in this stage, see section 7.5.1. The methane emissions were assumed to rise to the initial value of the unaffected mire. That is, the value assumed to be representative for the part of the mire that not previously had been affected by peat harvesting.

10.4.2 Afforestation

Since many of the peatlands/mires that historically have been used for peat harvesting are located in the southern part of Sweden, we assumed that the post harvesting forest productivity is quite high. In the simulations made, the productivity lie in the range of 7.5 – 10 m^3 sk/ha a.

The same assumptions concerning the emissions and uptake of CO_2 in biomass, humus and peat decomposition were used for these sites as for afforested cut-away sites that originally were pristine mires. Also for the methane and nitrous oxide emissions the same assumptions as in sections 7.5.2.2 and 7.5.2.3 were used.

10.5 Summary of parameter assumptions for simulations of radiative forcing from energy peat utilisation from old peat harvesting areas

In Table 10.1 a description of the different scenarios made for peat utilisation from old peat harvesting areas is given. The first column describes what type of peat (energy peat or peat litter for livestock rearing) that is assumed to have been harvested previously and the state of the drainage ditches before the start of the modern peat harvesting. The two columns with emissions from the site before modern harvesting gives the value for the unaffected area / affected area respectively. The denotation in the restoration column is similar to previous tables (i.e.Table 7.6, Table 8.1 and Table 9.2).

Table 10.1. Summary of parameter assumptions for simulations of radiative forcing resulting from energy peat utilisation from old peat harvesting areas.

Original mire/land-use	**Emissions before harvesting, un-harvested site /harvested site**		**Restoration**	**Comment**
Marsh Andromeda, 20% Peat litter for livestock rearing harvested.	8 / 12 g CH_4/m^2 a	-77 / -154 g CO_2/m^2 a	Re-wetting, 8 g CH_4/m^2a, CO_2 = -363 g CO_2/m^2a	Region 1-IV
	8 / 12 g CH_4/m^2 a	-77 / -154 g CO_2/m^2 a	Afforestation, rotation = 80 yr., 7.5 m^3 sk/ha a, 866.3 g CO_2/m^2a	
	8 / 12 g CH_4/m^2 a	-77 / -154 g CO_2/m^2 a	Afforestation, rotation 70 yr., 10 m^3 sk/ha a, 1155 g CO_2/m^2a	
Marsh Andromeda, 20% harvested. Peat litter for livestock rearing harvested.	3.5/10.5 g CH_4/m^2 a	-77 / -154 g CO_2/m^2 a	Re-wetting, 3.5 g CH_4/m^2a, CO_2 = -363 g CO_2/m^2a	Region 2
	3.5/10.5g CH_4/m^2 a	-77 / -154 g CO_2/m^2 a	Afforestation, rotation = 80 yr., 7.5 m^3 sk/ha a, 866.3 g CO_2/m^2a	
	3.5 / 10.5 g CH_4/m^2 a	-77 / -154 g CO_2/m^2 a	Afforestation, rotation 70 yr., 10 m^3 sk/ha a, 1155 g CO_2/m^2a	
Low sedge, 20% harvested. Peat litter for livestock rearing harvested. Drainage put out of running	6/39 g CH_4/m^2 a	-62 / -124 g CO_2/m^2 a	Re-wetting, 6 g CH_4/m^2a, CO_2 = -363 g CO_2/m^2a	Region 1-IV
	6/39 g CH_4/m^2 a	-62 / -124 g CO_2/m^2 a	Afforestation, rotation = 80 yr., 7.5 m^3 sk/ha a, 866.3 g CO_2/m^2a	
	6/39 g CH_4/m^2 a	-62 / -124g CO_2/m^2 a	Afforestation, rotation 70 yr., 10 m^3 sk/ha a, 1155 g CO_2/m^2a	
Low sedge, 20% harvested. Peat litter for livestock rearing harvested. Drainage put out of running	5.5/18.5 g CH_4/m^2 a	-62 / -124 g CO_2/m^2 a	Re-wetting, 5.5 g CH_4/m^2a, CO_2 = -363 g CO_2/m^2a	Region 3-II
	5.5/18.5 g CH_4/m^2 a	-62 / -124 g CO_2/m^2 a	Afforestation, rotation = 90 yr., 5.5 m^3 sk/ha a, 635.5 g CO_2/m^2a	
	5.5/18.5 g CH_4/m^2 a	-62 / -124 g CO_2/m^2 a	Afforestation, rotation = 90 yr., 7.5 m^3 sk/ha a, 866.3 g CO_2/m^2a	
Marsh Andromeda, 20% harvested. Energy peat harvested. Drainage not put out of running.	3.5/0 g CH_4/m^2 a	0 / 500 g CO_2/ m^2a	Re-wetting, 10 g CH_4/m^2a, CO_2 = -363 g CO_2/m^2a	Region 2
	3.5/0 g CH_4/m^2 a	0 / 500 g CO_2/ m^2a	Afforestation, rotation = 80 yr., 7.5 m^3 sk/ha a, 866.3 g CO_2/m^2a	
	3.5/0 g CH_4/m^2 a	0 / 500 g CO_2/ m^2a	Afforestation, rotation 70 yr., 10 m^3 sk/ha a, 1155 g CO_2/m^2a	
Marsh Andromeda, 20% harvested. Energy peat harvested. Drainage not put out of running.	8/0 g CH_4/m^2 a	0 / 500 g CO_2/ m^2a	Re-wetting, 8 g CH_4/m^2a, CO_2 = -363 g CO_2/m^2a	Region 1-IV
	8/0 g CH_4/m^2 a	0 / 500 g CO_2/ m^2a	Afforestation, rotation = 80 yr., 7.5 m^3 sk/ha a, 866.3 g CO_2/m^2a	
	8/0 g CH_4/m^2 a	0 / 500 g CO_2/ m^2a	Afforestation, rotation 70 yr., 10 m^3 sk/ha a, 1155 g CO_2/m^2a	

11 Results – climate impact of peatlands with different land-use history

The calculated climate impacts of the different scenarios described in previous chapters are presented in the sections below. Each of the four types of peatlands (with the different land-use history) are presented in a separate section. In most of the figures describing the results, the corresponding climate impact of using coal and natural gas are given as references.

In the figures with accumulated emissions, a negative value means a net uptake of the gas and a positive value means net emissions.

11.1 Utilisation of pristine mires for energy peat production

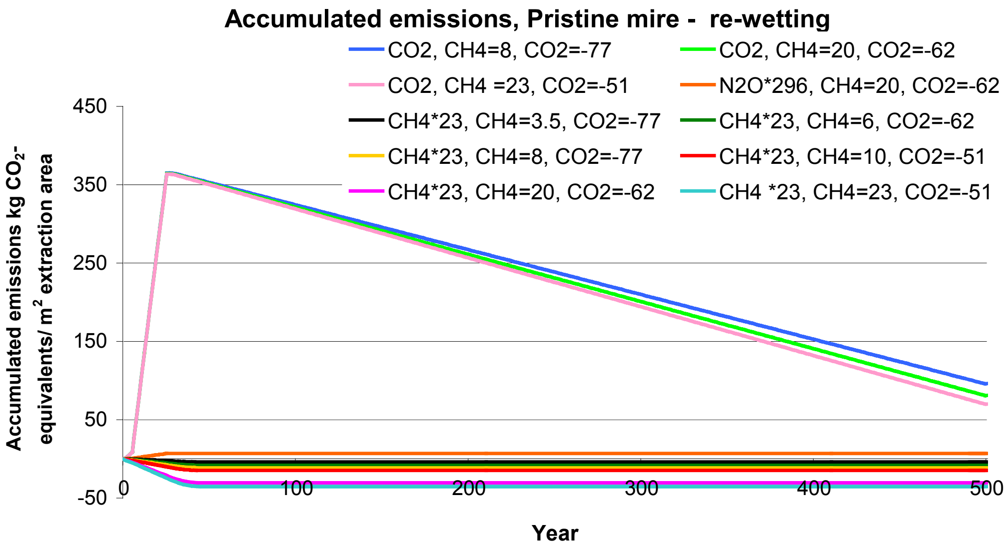


Figure 11.1. The accumulated emissions of CO_2, CH_4 and N_2O for the scenarios describing the sequence of pristine mire - peat harvesting - rewetting. The scenarios are named by the initial emission/uptake of greenhouse gases. CH_4 = XX, is the value of the original methane emissions from the pristine mire [g CH_4/m^2a]. CO_2= XX, is the value of the original CO_2 uptake at the pristine mire [g CO_2/m^2a]. The first section of the name tells what gas it represents. As the name indicates the methane emissions have been multiplied by a factor of 23 and the nitrous oxide emissions have been multiplied by a factor of 296, those factors are the GWP_{100} values for the gases respectively as given in Houghton et al (2001). The N_2O emissions are the same in all scenarios and are therefore only displayed by one line.

The re-wetted sites have methane and nitrous oxide emissions of the same level as the original peatland, which explains why the accumulated emissions level out (quite soon after the end of harvesting). The CO_2 net uptake of the new wetland will be higher than the net uptake at the mature original peatland, which explains the decreasing trend of the accumulated CO_2 emissions after the rewetting event.

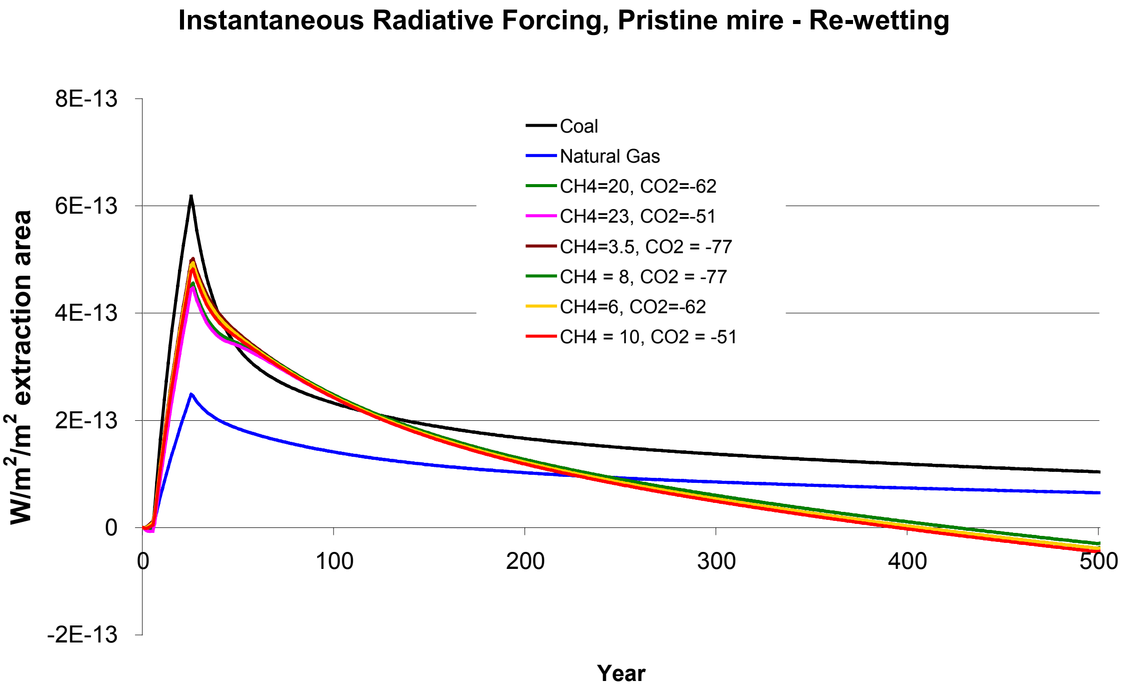


Figure 11.2. The instantaneous radiative forcing of the scenarios of the pristine –extraction - rewetting sequence. The scenarios represent the total instantaneous radiative forcing of all three gases together. Since it is assumed that the methane production eventually will reach the pre-harvesting level there are only three different levels of instantaneous radiative forcing after a longer time period, depending on the initial uptake of CO_2. The scenarios have been named as in Figure 11.1 but here each scenario represents the instantaneous radiative forcing of all three gases together.

The dominating factor explaining the difference between the climate impact of the different peatland scenarios, as presented in Figure 11.2 & Figure 11.3, and coal during the first 50 years is the effect of the avoided methane emissions. Since we assume that the re-wetted peatland will reach similar methane emissions as the pristine mire the effect of the loss of carbon uptake will be the dominating factor in the long run. This is the explanation to why the scenarios with the smallest loss in carbon uptake will have the smallest climate impact in the long run and not the scenarios with the largest amount of avoided methane emissions. The reason why the peat scenarios decline compared to both the coal and the natural gas scenarios is that the re-wetted site have a net carbon uptake. The scenario with the lowest potential climate impact, (accumulated radiative forcing, Figure 11.3) is just a comparative scenario where we assume that the methane emissions at the re-wetted site will be lower than at the pristine mire. The initial value was 23 g CH_4/m^2a and the value at the re-wetted site was 10 g CH_4/m^2a. This scenario shows that reducing the methane emissions at the re-wetted site can have a significant impact.

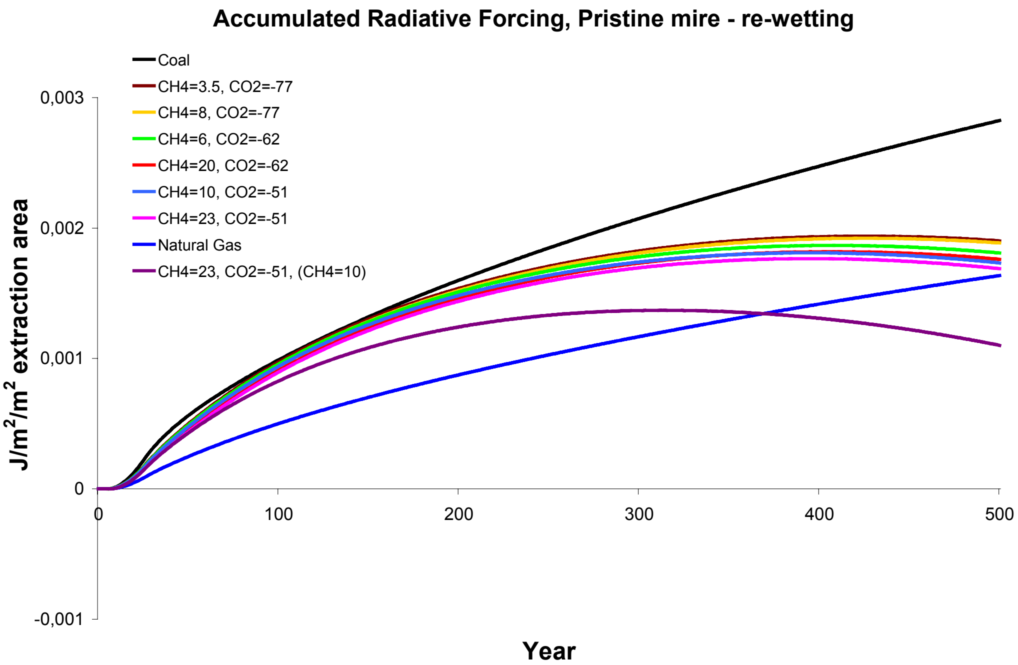


Figure 11.3. Accumulated radiative forcing due to harvesting of energy peat from an originally pristine mire and site restored to a wetland/peatland. The CH_4=10 in brackets at the lowest scenario means that the methane emissions after rewetting have been assumed to this level.

The methane emissions at the afforested site have been assumed to be negligible and that is the explanation for the decreasing trend of the accumulated methane emissions in Figure 11.4. Only the first rotation of the forest production is considered. After that there is no net uptake of CO_2, which explains why the accumulated CO_2 emissions first decreases after the combustion and then after approximately 80 years (the length of one rotation) increases again. The rising trend of the accumulated CO_2 emissions is caused by the decomposition of the remaining peat layer both at the extraction and the surrounding area. There is also an increasing trend of the N_2O emissions, which is due to the higher emissions from an afforested site compared to a pristine mire.

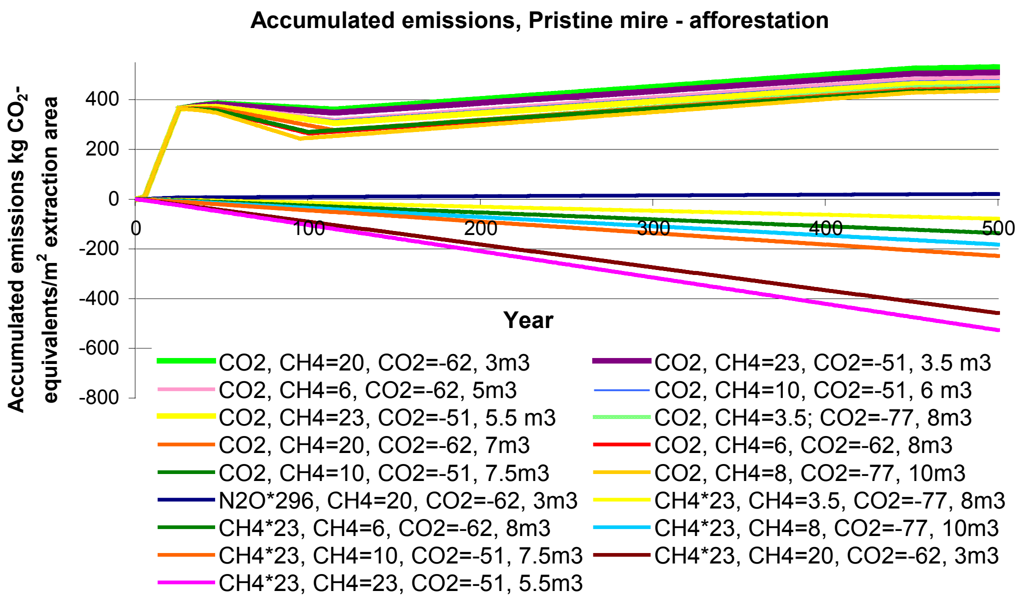


Figure 11.4 The accumulated emissions of CO_2, CH_4 and N_2O for the system pristine mire, peat harvesting - afforestation. The legend is similar to the legend in the previous figures of this section. The post-harvesting forest productivity is indicated at the end of the scenario names. The nitrous oxide and the methane emissions are not affected by the forest productivity.

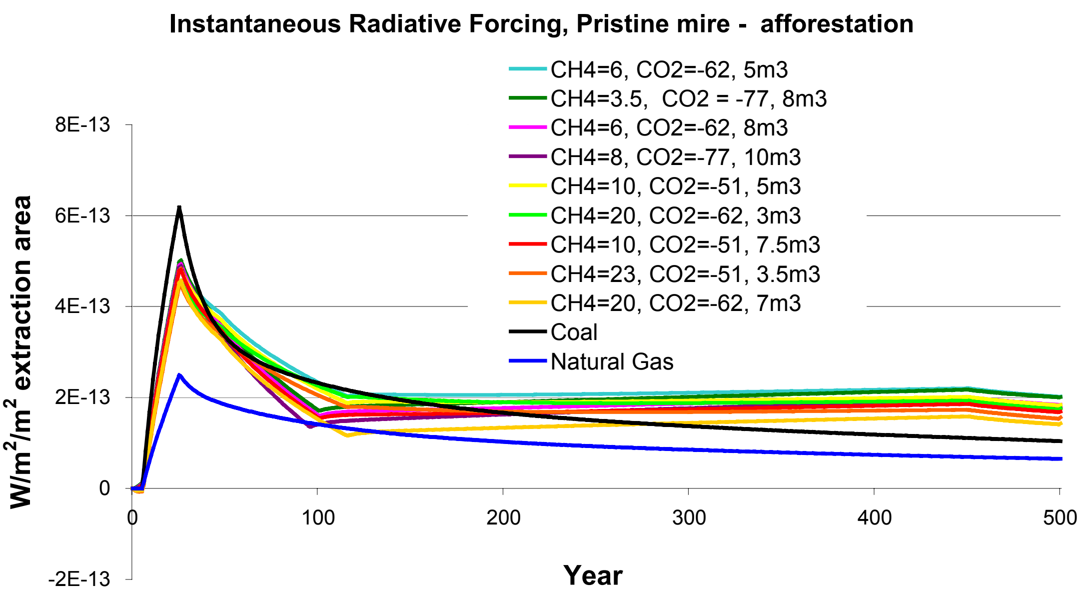


Figure 11.5. The instantaneous radiative forcing of the pristine –peat harvesting - afforestation sequence. The scenarios are described by the initial emissions/uptake of CH_4 and CO_2. The numbers at the end of the scenarios names [m^3] tell the post-harvesting forest productivity.

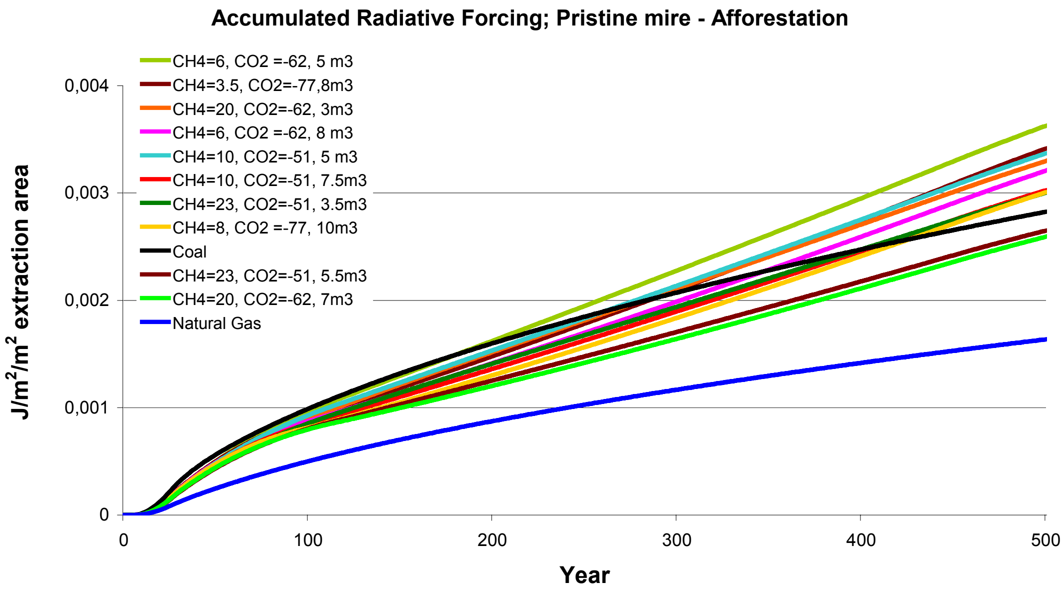


Figure 11.6 Accumulated radiative forcing due to extraction of energy peat from an originally pristine mire and site restored by afforestation.

The reason for the rising trend in the climate impact from the pristine- peat harvesting - afforestation systems (Figure 11.6) is that once the forest is mature no more CO_2 is sequestered into the system. At the same time the remaining peat layer at the surrounding area continues to oxidise. The pristine mire had a continuous net accumulation of CO_2. It should be noted that the long time average values of CO_2 sequestration for peatlands are used, which in fact could overestimate the present rate of CO_2 net uptake. A further explanation for the rising trend is the continuous emissions of nitrous oxide. Figure 11.7 and Figure 11.8 below show the effect of different rate of carbon sequestration, forest productivity and avoided methane emissions respectively. In Figure 11.7 the effects of forest productivity and the effect of different levels of avoided methane emissions are illustrated. In scenarios, with higher levels of initial methane emissions and/or forest productivity the effect of forest productivity is of greater importance. Both effects are of importance already after a short period. In Figure 11.8 the effect of initial CO_2 uptake in pristine mires is illustrated. It shows that during the first 100 years the effect is < 2% (i.e. the total accumulated radiative forcing differed less than 2% between a mire with the long-term average CO_2 uptake and a mire with no CO_2 uptake at all) and not until 200 years after harvesting the effect is > 5%. Hence that effect will not be significant in a short time perspective.

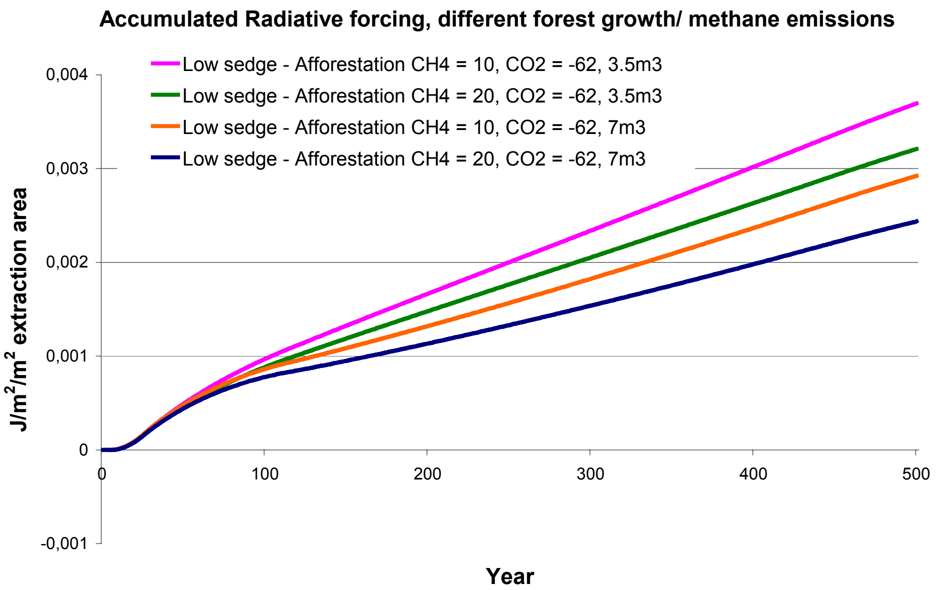


Figure 11.7. The effect of forest productivity and avoided methane emissions respectively. The denotation of the scenarios is the same as in previous figures.

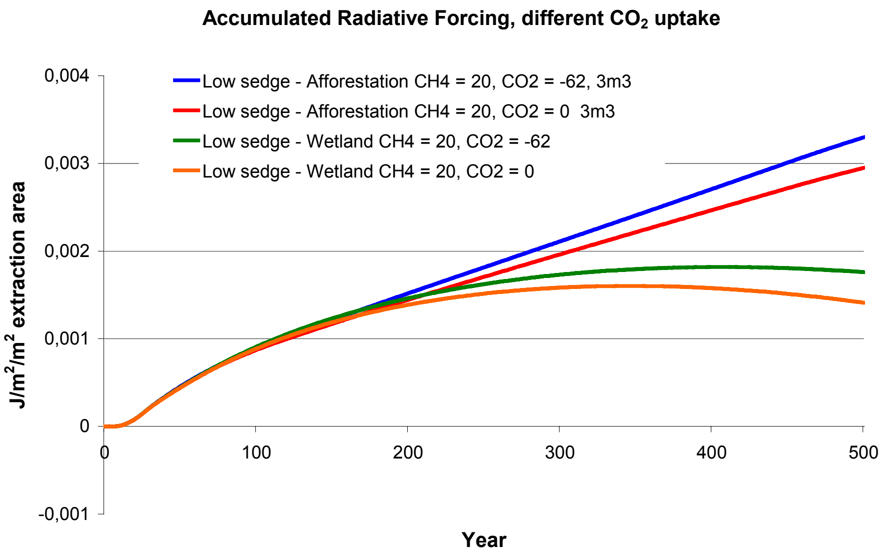


Figure 11.8. The effect of different carbon uptake in the pristine mire. The effect is quite small in a shorter time perspective but of importance in the long run. It is assumed that the methane emissions in the new wetland will reach the same level as in the original pristine mire.

In Table 11.1 the numerical values of the accumulated radiative forcing of the different scenarios of pristine mires (different original methane emissions, forest productivity and carbon dioxide uptake) are given for 100 and 300 years respectively. Both total values and the individual contribution by the different gases (CO_2, CH_4 and N_2O) are given.

Table 11.1. Accumulated radiative forcing for the pristine mire scenarios at 100 and 300 years respectively. [J/m²/m²extraction area]

Land-use	Total Accumulated Radiative Forcing		Accumulated Radiative Forcing					
	t = 100	t=300	CO_2, t=100	CO_2, t= 300	CH_4, t=100	CH_4, t = 300	N_2O, t= 100	N_2O, t= 300
CH_4=20, CO_2=-62	9.10E-04	1.73E-03	9.62E-04	1.77E-03	-6.57E-05	-6.59E-05	1.71E-05	2.98E-05
CH_4=20, CO_2=-62, 3m^3	8.95E-04	2.11E-03	1.05E-03	2.63E-03	-1.71E-04	-5.71E-04	2.03E-05	5.45E-05
CH_4=20, CO_2=-62, 7m^3	7.98E-04	1.64E-03	9.51E-04	2.16E-03	-1.71E-04	-5.71E-04	2.03E-05	5.45E-05
CH_4=6, CO_2=-62	9.58E-04	1.78E-03	9.62E-04	1.77E-03	-1.74E-05	-1.75E-05	1.71E-05	2.98E-05
CH_4=6, CO_2=-62, 8m^3	8.74E-04	1.99E-03	9.05E-04	2.11E-03	-4.90E-05	-1.69E-04	2.03E-05	5.45E-05
CH_4=6, CO_2=-62, 5 m^3	9.68E-04	2.28 E-03	1.00E-03	2.40E-03	-4.90E-05	-1.69 E-04	2.03E-05	5.45E-05
CH_4 =23, CO_2=-51	8.96E-04	1.70E-03	9.58E-04	1.74E-03	-7.57E-05	-7.59E-05	1.71E-05	2.98E-05
CH_4 =23, CO_2=-51, 3.5m^3	8.53E-04	1.94E-03	1.03E-03	2.55E-03	-1.97E-04	-6.57E-04	2.03E-05	5.45E-05
CH_4 =23, CO_2=-51, 5.5m^3	8.05E-04	1.71E-03	9.84E-04	2.31E-03	-1.97E-04	-6.57E-04	2.03E-05	5.45E-05
CH_4 =10, CO_2=-51	9.40E-04	1.74E-03	9.58E-04	1.74E-03	-3.16E-05	-3.17E-05	1.71E-05	2.98E-05
CH_4 =10, CO_2=-51, 5m^3	9.29E-04	2.14E-03	9.96E-04	2.37E-03	-8.42E-05	-2.84E-04	2.03E-05	5.45E-05
CH_4 =10, CO_2=-51, 7.5m^3	8.47E-04	1.90E-03	9.13E-04	2.13E-03	-8.42E-05	-2.84E-04	2.03E-05	5.45E-05
CH_4=8, CO_2=-77	9.56E-04	1.81E-03	9.67E-04	1.80E-03	-2.45E-05	-2.46E-05	1.71E-05	2.98E-05
CH_4=8, CO_2=-77, 10m^3	8.15E-04	1.84E-03	8.63E-04	2.01E-03	-6.66E-05	-2.27E-04	2.03E-05	5.45E-05
CH_4=3.5, CO_2=-77	9.72E-04	1.83E-03	9.67E-04	1.80E-03	-8.58E-06	-8.60E-06	1.71E-05	2.98E-05
CH_4=3.5, CO_2=-77, 8m^3	9.01E-04	2.10E-03	9.10E-04	2.14E-03	-2.70E-05	-9.70E-05	2.03E-05	5.45E-05
Total variation	**7.98 – 9. 72E-04**	**1.64 – 2. 28E-03**						
Rewetting	$8.96 – 9.72 \cdot 10^{-4}$	$1.70 – 1.83 \cdot 10^{-3}$						
Afforestation	$7.98– 9.29 \cdot 10^{-4}$	$1.64 – 2.28 \cdot 10^{-3}$						

11.2 Utilisation of agricultural peatlands for energy peat production

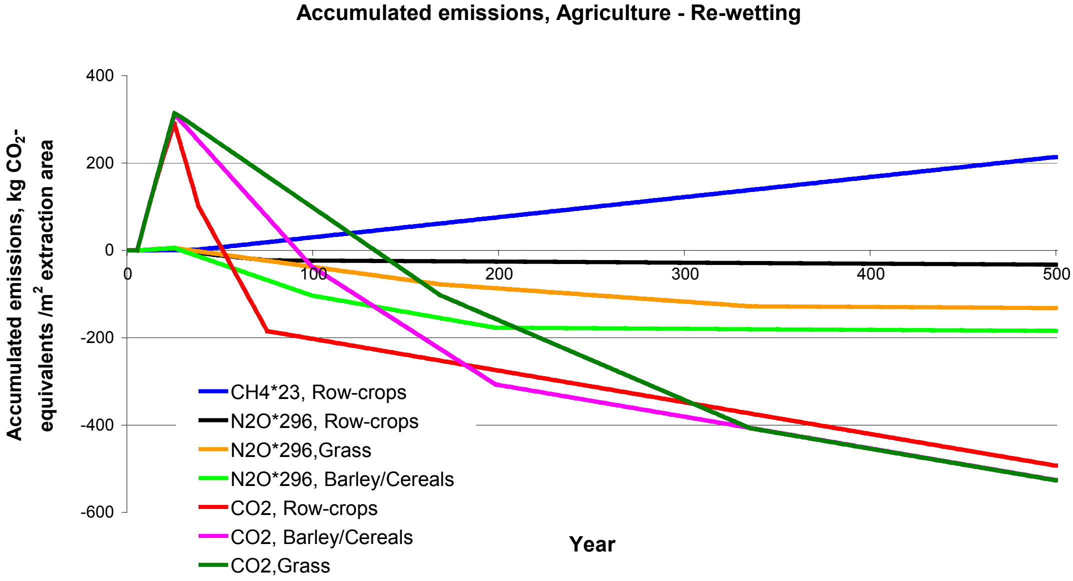


Figure 11.9 The accumulated emissions from the agricultural – rewetting scenarios. Note that the N_2O emissions are multiplied by a factor of 296 and the CH_4 emissions by a factor of 23 (the GWP_{100} factors for the gases respectively). The scenarios are named by the cropping system at the agricultural land, see Table 8.1 for a detailed description of the scenarios.

Since there are initially quite large emissions of both carbon dioxide and nitrous oxide from the agricultural peatlands (Figure 11.9) there is a decreasing trend of the accumulated emissions of those gases after the end of the combustion period. The reason for the curves to level out is that the original peat layer has decomposed completely within the studied period. This occurs earlier at the sites with a higher rate of oxidation (row-crops) than at sites with lower rate of oxidation. Note that the curves in the diagram represent the net effect of peat harvesting, i.e. the peat emission scenario – the reference scenario. Since rewetting will prevent the oxidation of the remaining peat layer and the reference scenario assumes complete oxidation of the peat the net effect will look very favourable from a climate impact point of view. However, there is not more carbon stored in the system after 500-600 years than there was before the peat harvesting. The reason for the CO_2 emissions of the row-crop scenario (in Figure 11.9) to level out at a higher level than the barley and grass scenarios (smaller negative value) is the high oxidation rate assumed to prevail during the harvesting period. Due to this a larger amount of peat will oxidise during the harvesting stage and less will be prevented from oxidising in the re-wetted stage. This is also the explanation to why the row-crop scenario also in Figure 11.10 and Figure 11.11 is the one with the largest climate impact in the long run.

Rewetting also leads to methane emissions and in this study it is assumed that no methane emissions occurred at the agricultural field. This is why the accumulated methane emissions increase continuously.

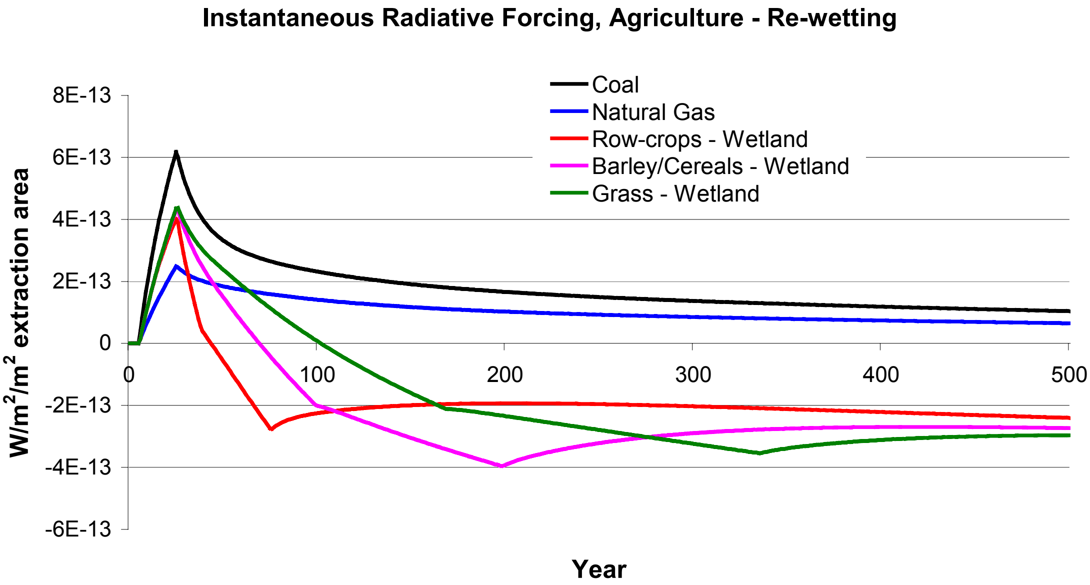


Figure 11.10. The instantaneous radiative forcing of the agricultural – peat harvesting – rewetting scenarios. The scenarios are named by the initial cropping system of the agricultural fields. See Table 8.1 for a description of the scenarios.

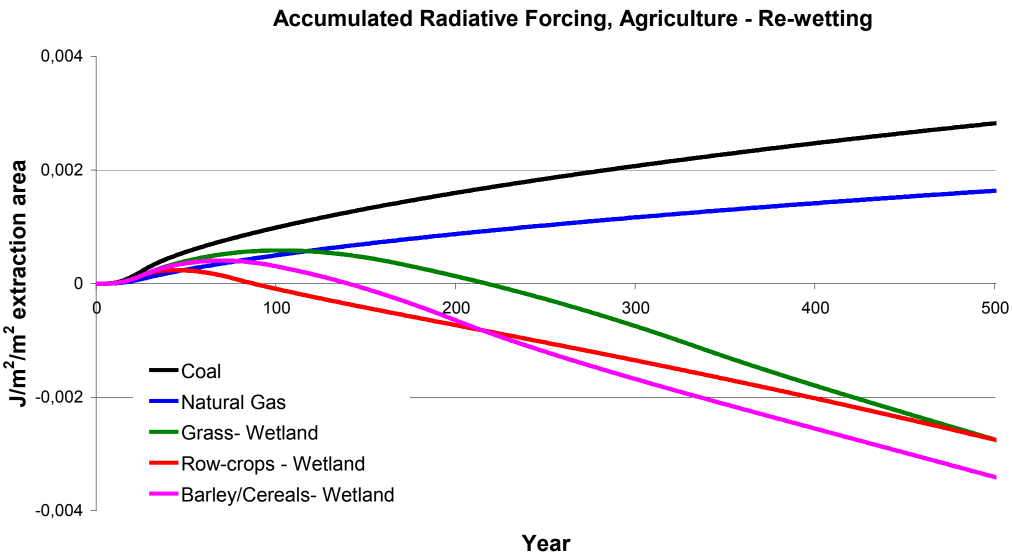


Figure 11.11. Accumulated radiative forcing for the agricultural – peat harvesting - rewetting scenarios. The assumed level of CH_4 emissions after re-wetting is 10 g CH_4/m^2a.

Both the instantaneous and the accumulated radiative forcing indicate that these scenarios already after 50-150 years will result in a lower climate impact than natural gas and after 100 – 200 years even result in a positive climate impact (i.e. negative radiative forcing = cooling effect).

As can be seen in Figure 11.12 the CO_2 emissions in the agricultural peatland – peat harvesting - afforestation scenarios decrease relatively rapidly after the end of combustion period and level out on a negative value due to the net uptake of the forest. The scenarios with a high initial oxidation rate level out sooner than the other scenarios. The reason is that the peat in the reference case (continuing cropping) would have been completely decomposed at an earlier stage. The methane emissions (Figure 11.13) have little impact on the scenarios by being low in all cases. The effect of nitrous oxide emissions (Figure 11.13) depends on the rate of oxidation of the peat layer.

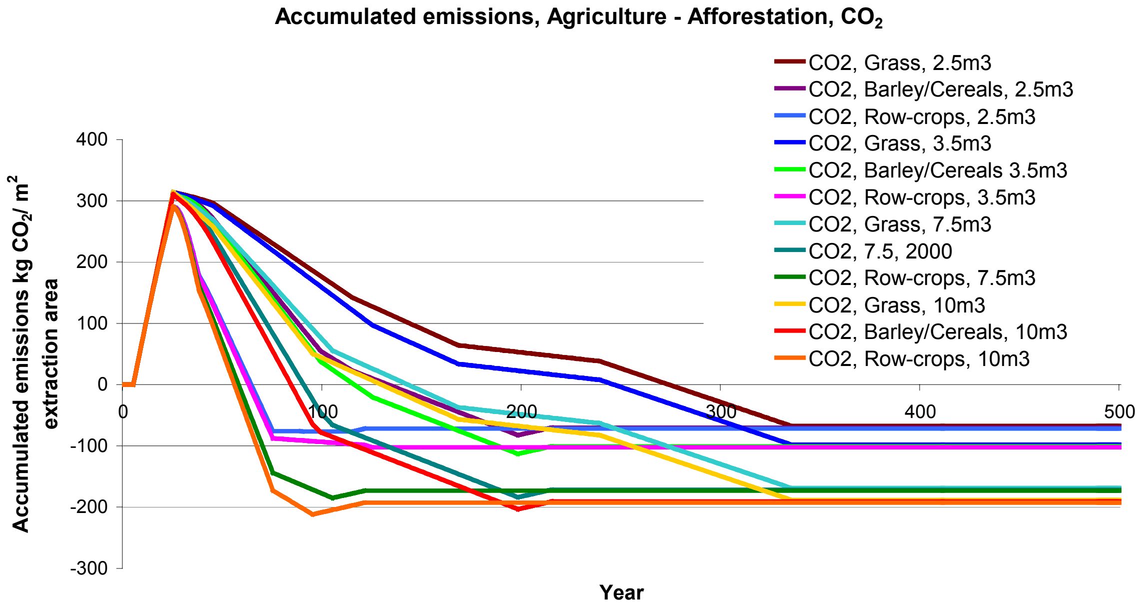


Figure 11.12 The accumulated emissions of the afforestation scenarios of the agricultural peatlands.

Like the scenarios for the agricultural peatland – peat harvesting - re-wetting scenarios the scenarios for agricultural peatland – peat harvesting - afforestation (Figure 11.14 and Figure 11.15) give a smaller climate impact than natural gas after 50 – 150 years. The effect of avoided emissions of nitrous oxide is not as great as in the re-wetting scenarios and there are no methane emissions that will add to the radiative forcing.

In Table 11.2 the numerical values of the accumulated radiative forcing of the different scenarios for the agricultural peatlands are given for 100 and 300 years respectively. Both total values and the individual contribution by the different gases (CO_2, CH_4 and N_2O) are given.

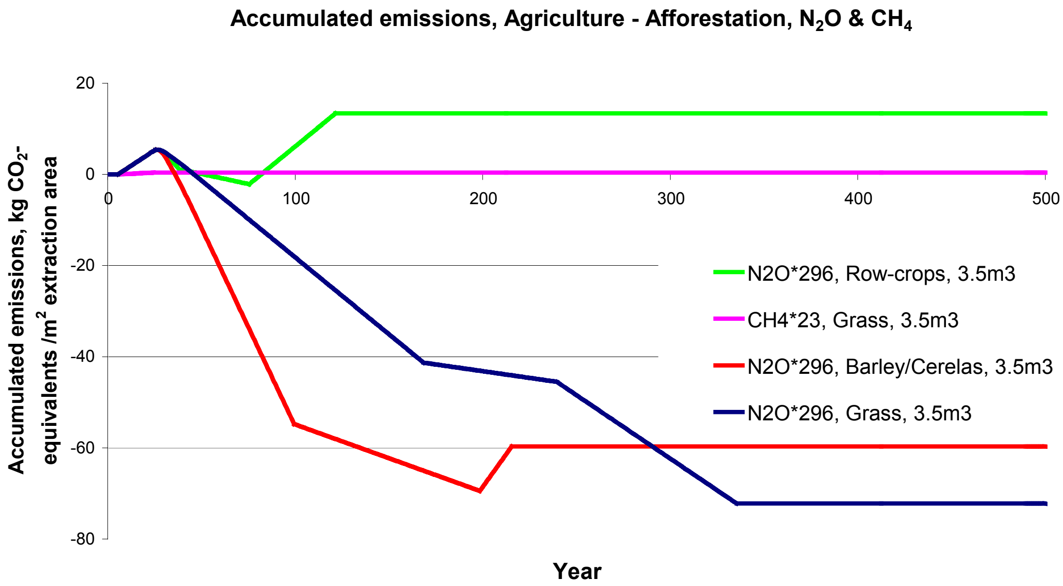


Figure 11.13 The accumulated nitrous oxide and methane emissions of the afforestation scenarios of the agricultural peatlands. The methane emissions are negligible in these scenarios. The emissions of nitrous oxide will continue until the peat layer has oxidised completely. This will take longer time at the surrounding area in the case of peat extraction and the emissions of nitrous oxide will stay relatively high during the whole process. This is the explanation to why there is a net effect of emissions in the case of the row-crops scenario where the initial oxidation rate is extremely high.

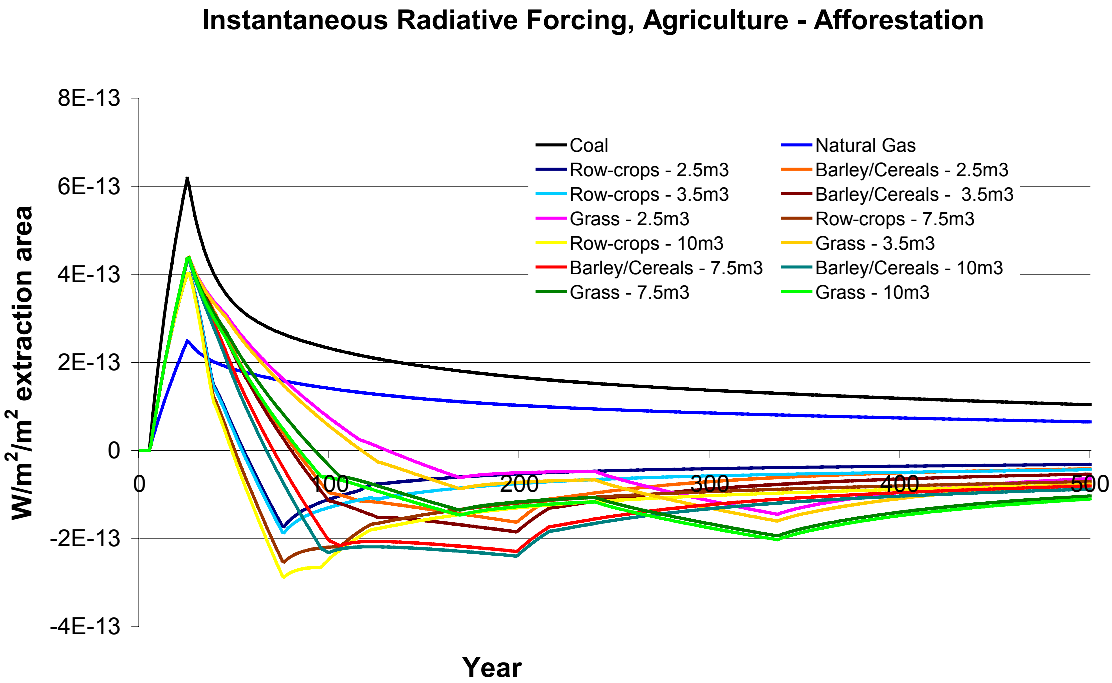


Figure 11.14. The instantaneous radiative forcing of the agricultural –harvesting – afforestation scenarios. Note that the scenarios are ordered from highest to lowest at time 250 in the legend.

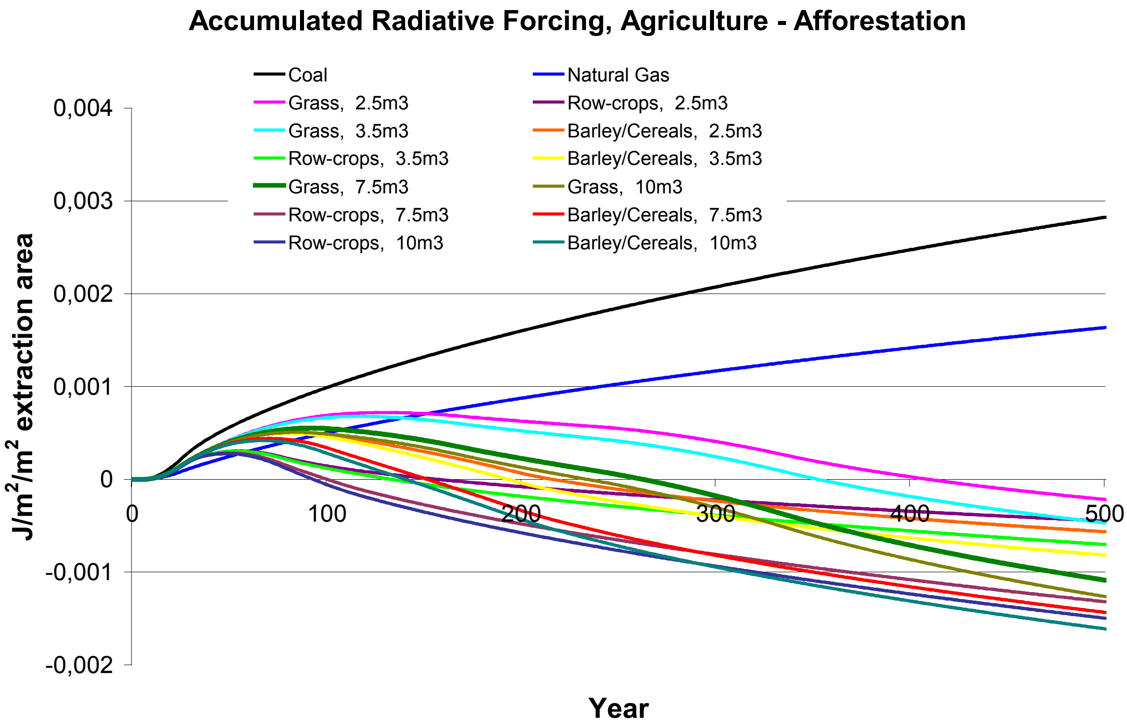


Figure 11.15. Accumulated radiative forcing for the agricultural – peat harvesting - afforestation system., Xm^3 indicates the assumed forest productivity [m^3sk/ha a] of the afforested site. The rate of oxidation is depending on cropping system; 1100 g CO_2/m^2a = grass, 2000 g CO_2/m^2a = cereals/barley; 7000 g CO_2/m^2a= row crops.

Table 11.2. Accumulated Radiative Forcing for Agricultural peatlands scenarios at 100 and 300 years respectively. [J/m^2/m^{2}extraction area]

Land-use	Total Accumulated Radiative Forcing		Accumulated Radiative Forcing					
	t = 100	t=300	CO_2, t=100	CO_2, t= 300	CH_4, t=100	CH_4, t = 300	N_2O, t= 100	N_2O, t= 300
Grass -Wetland	5.85E-04	-7.51E-04	5.73E-04	-6.35E-04	5.35E-05	2.53E-04	-4.14E-05	-3.75E-04
Grass, 3.5m^3	6.65E-04	2.44E-04	6.80E-04	4.27E-04	8.63E-07	8.64E-07	-1.51E-05	-1.86E-04
Grass, 2.5 m^3	6.89E-04	4.07E-04	7.05E-04	5.91E-04	8.63E-07	8.64E-07	-1.51E-05	-1.86E-04
Grass, 7.5 m^3	5.47E-04	-1.78E-04	5.61E-04	4.38E-06	8.63E-07	8.64E-07	-1.51E-05	-1.86E-04
Grass, 10 m^3	4.88E-04	-3.05E-04	5.01E-04	-1.23E-04	8.63E-07	8.64E-07	-1.51E-05	-1.86E-04
Cereals/Barely– Wetland	3.04E-04	-1.68E-03	3.73E-04	-1.26E-03	5.35E-05	2.53E-04	-1.25E-04	-6.82E-04
Cereals/Barley, 3.5 m^3	4.58E-04	-3.98E-04	5.15E-04	-1.51E-04	8.63E-07	8.64E-07	-5.97E-05	-2.49E-04
Cereals/Barley, 2.5 m^3	4.82E-04	-2.34E-04	5.40E-04	1.31E-05	8.63E-07	8.64E-07	-5.97E-05	-2.49E-04
Cereals/Barley, 7.5 m^3	3.40E-04	-8.19E-04	3.95E-04	-5.73E-04	8.63E-07	8.64E-07	-5.97E-05	-2.49E-04
Cereals/Barley, 10 m^3	2.81E-04	-9.46E-04	3.36E-04	-7.00E-04	8.63E-07	8.64E-07	-5.97E-05	-2.49E-04
Row-crops – Wetland	-9.39E-05	-1.35E-03	-1.15E-04	-1.50E-03	5.35E-05	2.53E-04	-3.58E-05	-1.09E-04
Row-crops, 3.5 m^3	1.19E-04	-3.88E-04	1.12E-04	-4.42E-04	8.63E-07	8.64E-07	3.61E-06	5.23E-05
Row-crops, 2.5 m^3	1.43E-04	-2.24E-04	1.37E-04	-2.78E-04	8.63E-07	8.64E-07	3.61E-06	5.23E-05
Row-crops, 7.5 m^3	6.53E-07	-8.10E-04	-7.28E-06	-8.65E-04	8.63E-07	8.64E-07	3.61E-06	5.23E-05
Row-crops, 10 m^3	-5.84E-05	-9.37E-04	-6.67E-05	-9.91E-04	8.63E-07	8.64E-07	3.61E-06	5.23E-05
Total variation	**$-9.39 \cdot 10^{-5}$–$6.89 \cdot 10^{-4}$**	**$-1.68 \cdot 10^{-3}$ – $4.07 \cdot 10^{-4}$**						
Variation Rewetting	$-9.39 \cdot 10^{-5}$– $5.85 \cdot 10^{-4}$	$-1.68 \cdot 10^{-3}$ – $-7.51 \cdot 10^{-4}$						
Variation Afforestation	$-5.84 \cdot 10^{-5}$ - $6.89 \cdot 10^{-4}$	$-9.46 \cdot 10^{-4}$ – $-4.07 \cdot 10^{-4}$						

11.3 Utilisation of drained forested peatlands for energy peat production

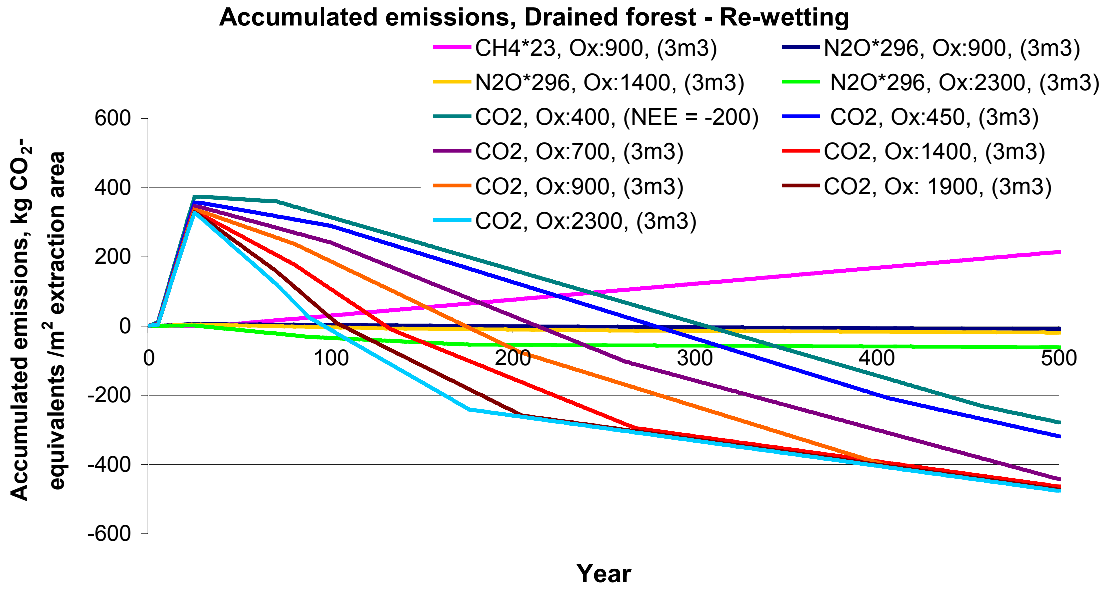


Figure 11.16 The accumulated emissions of CO_2, CH_4 and N_2O for the scenarios describing a system of drained forested peatland - peat extraction - rewetting. As the legend indicates the methane emissions have been multiplied by a factor of 23 and the nitrous oxide emissions have been multiplied by a factor of 296. Those factors are the GWP_{100} values for that gases The Ox: XXX tells the initial rate of oxidation at the drained forest and the number in brackets tells the assumed forest productivity before the harvesting.

Since the methane emissions from the drained forested peatlands are assumed to be negligible and the emissions from the re-wetted site are assumed to reach 10 g CH_4/m^2a there is a continuously rising trend of the accumulated methane emissions for all of the re-wetting scenarios, Figure 11.16. In this study three different levels of N_2O emissions were used in the different scenarios, i.e. 0.08 (Ox: 900), 0.2 (Ox:1400) and 0.9 (Ox: 2300).

Figure 11.17 and Figure 11.18 show the instantaneous radiative forcing of the rewetting and afforestation scenarios respectively. It should be noted that the scenarios with an initial oxidation rate of >800 g CO_2/m^2a, and hence net emissions of CO_2 > 150 g C/m^2a, are not based on measurements of net CO_2 balances but rather estimates based on measured oxidation rates and low forest productivity. Non of the scenarios where the net CO_2 balance of the drained forest is based on actual measurements (oxidation rate < 900 g CO_2/m^2 a) are below the natural gas reference scenario until 200 – 250 years after restoration.

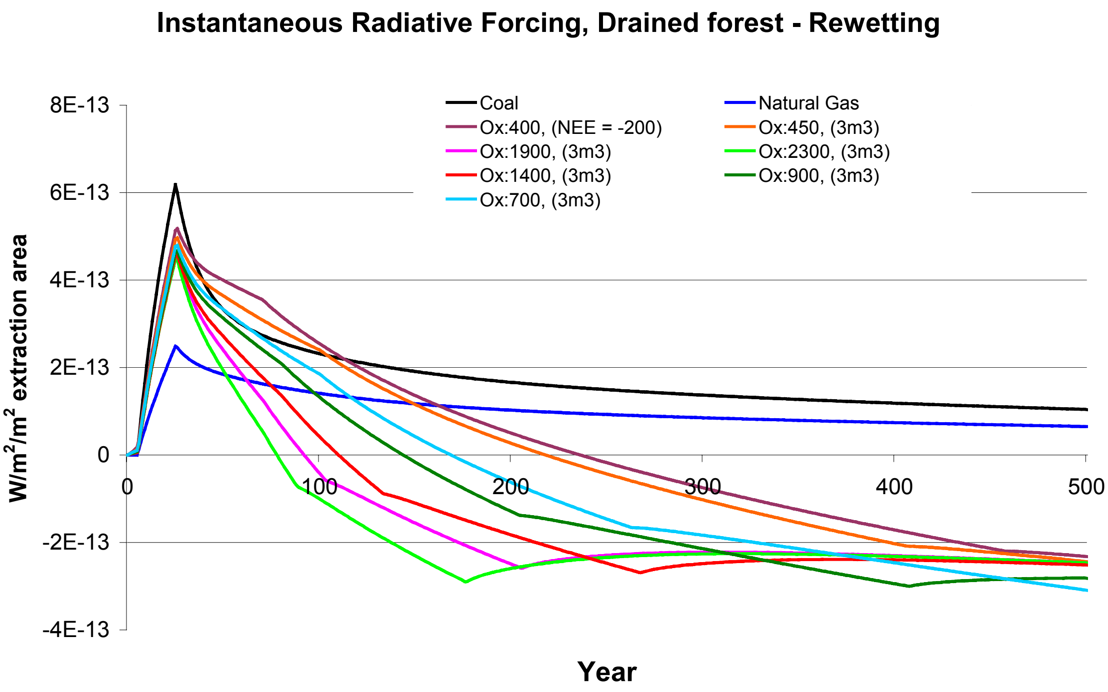


Figure 11.17. The instantaneous radiative forcing resulting from the drained forested peatland –peat harvesting - rewetting scenarios. The scenarios are named as in Figure 11.16.

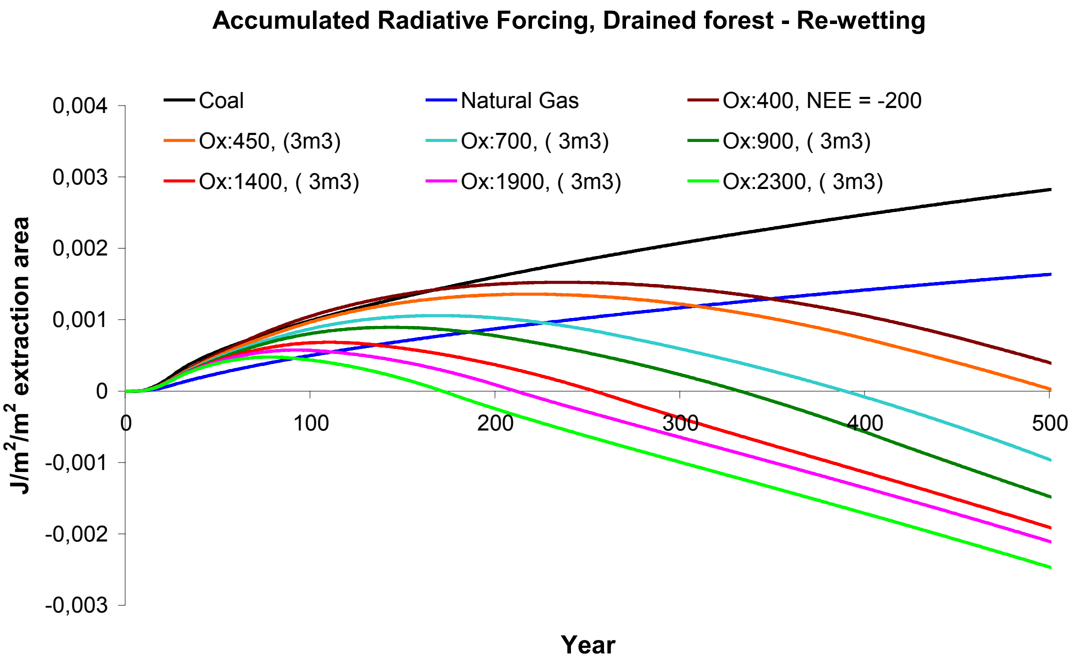


Figure 11.18. The total accumulated radiative forcing resulting from the drained forested peatland –peat harvesting - rewetting scenarios. The scenarios are named as in Figure 11.16.

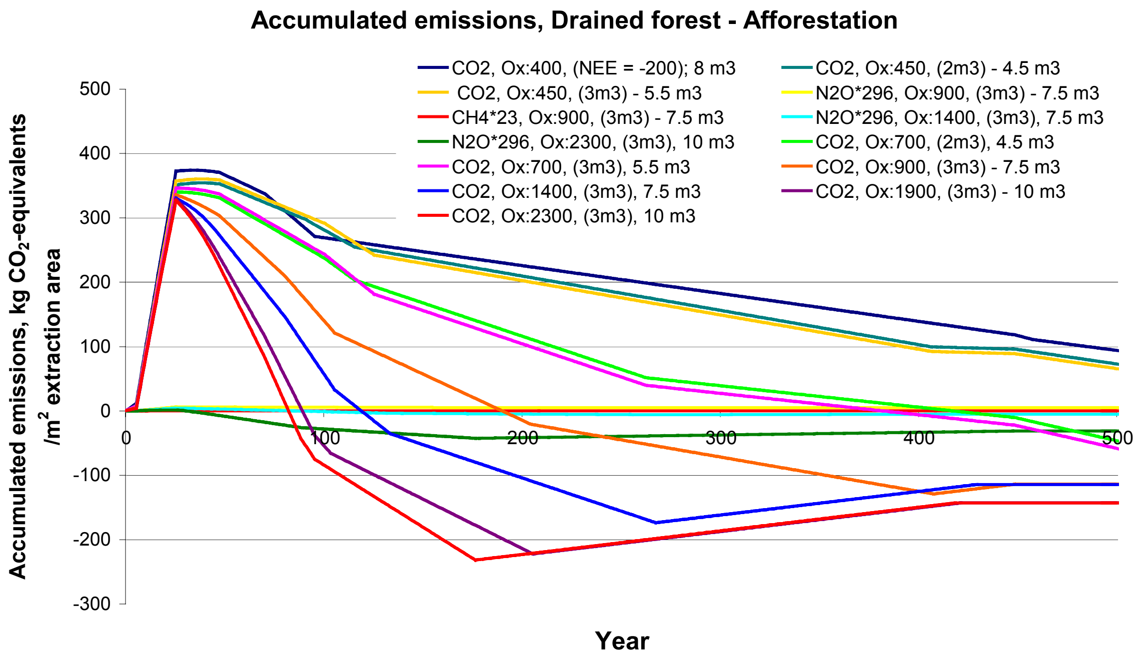


Figure 11.19 The accumulated emissions of CO_2, CH_4 and N_2O for the scenarios describing a sequence of drained forested peatland - peat harvesting - afforestation. The denotation of the different scenarios is analogous to the denotation in Figure 11.16. The last value of the scenario name indicates the forest productivity at the afforested sites (in m^3 sk). As in the re-wetting scenarios there is only one level of methane emissions and three levels of nitrous oxide emissions.

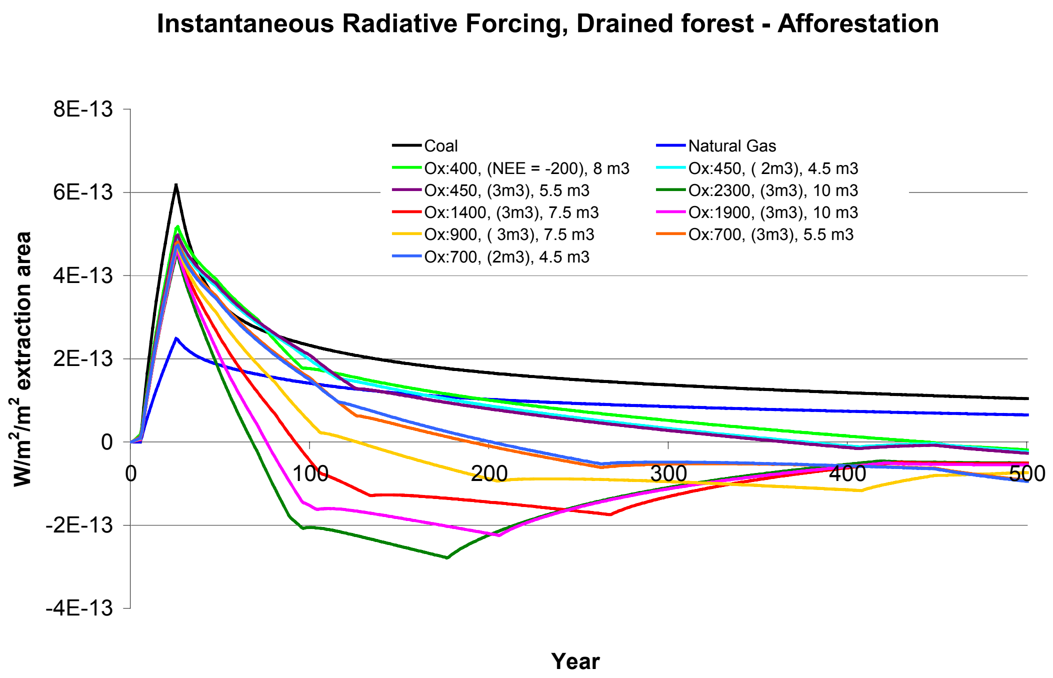


Figure 11.20. The instantaneous radiative forcing resulting from the drained forested peatland – peat harvesting - afforestation scenarios. The scenarios are named as in Figure 11.16.

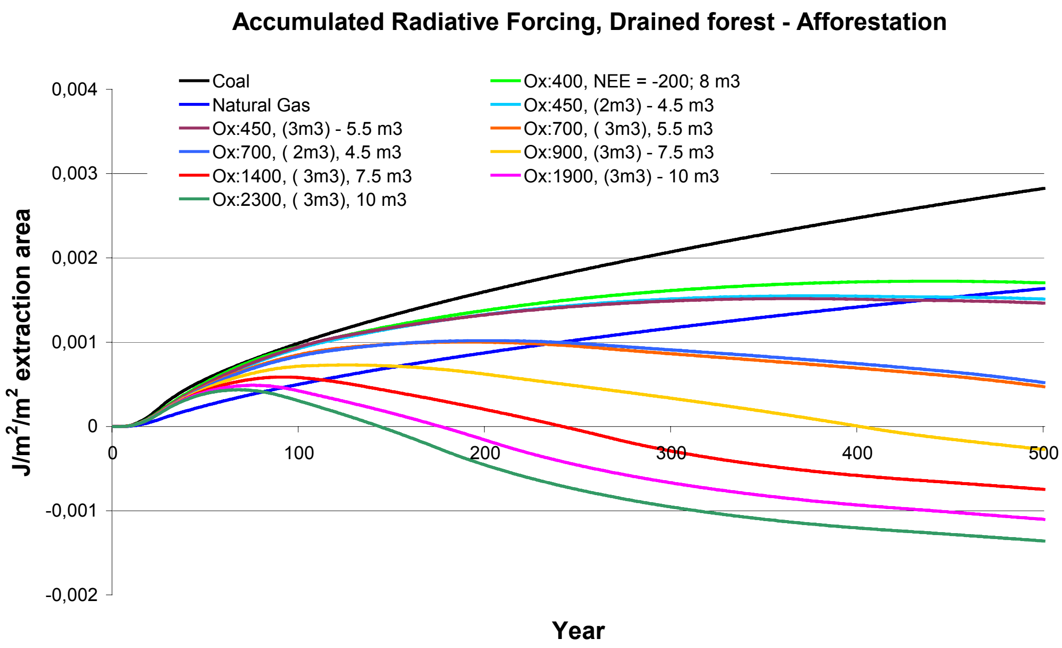


Figure 11.21. Total accumulated radiative forcing resulting from the drained forested peatland – peat harvesting - afforestation scenarios.

In Table 11.3 the values of the accumulated radiative forcing of the different scenarios is given for 100 and 300 years respectively.

Table 11.3. Accumulated Radiative Forcing for drained forested peatland scenarios at 100 and 300 years respectively. [J/m^2/m^{2}extraction area]

Land-use	Total Accumulated Radiative Forcing		Accumulated Radiative Forcing					
	t = 100	t=300	CO_2, t=100	CO_2, t= 300	CH_4, t=100	CH_4, t = 300	N_2O, t= 100	N_2O, t= 300
Ox:900, (3m^3)	8.07E-04	2.30E-04	7.44E-04	-2.52E-05	5.35E-05	2.53E-04	1.15E-05	-2.00E-06
Ox:900, (3m^3) - 7.5 m^3	7.14E-04	3.34E-04	7.00E-04	3.09E-04	8.63E-07	8.64E-07	1.46E-05	2.27E-05
Ox:1900, (3 m^3)	5.71E-04	-6.48E-04	5.05E-04	-9.06E-04	5.35E-05	2.53E-04	1.15E-05	8.74E-07
Ox:1900, (3 m^3) - 10 m^3	4.20E-04	-6.70E-04	4.03E-04	-6.98E-04	8.63E-07	8.64E-07	1.46E-05	2.55E-05
Ox:450, (3 m^3)	9.68E-04	1.22E-03	9.07E-04	9.67E-04	5.35E-05	2.53E-04	1.15E-05	-2.87E-06
Ox:450, (3 m^3) - 5.5 m^3	9.45E-04	1.49E-03	9.33E-04	1.47E-03	8.63E-07	8.64E-07	1.46E-05	2.18E-05
Ox:450, (2 m^3) - 4.5 m^3	9.27E-04	1.51E-03	9.15E-04	1.49E-03	8.63E-07	8.64E-07	1.46E-05	2.18E-05
Ox:400, NEE = -200	1.05E-03	1.45E-03	9.91E-04	1.20E-03	5.35E-05	2.53E-04	1.15E-05	-2.87E-06
Ox:400, NEE = -200; 8 m^3	9.48E-04	1.61E-03	9.36E-04	1.59E-03	8.63E-07	8.64E-07	1.46E-05	2.18E-05
Ox:1400, (3 m^3)	6.78E-04	-3.79E-04	6.24E-04	-5.92E-04	5.35E-05	2.53E-04	1.09E-06	-4.40E-05
Ox:1400, (3 m^3), 7.5 m^3	5.80E-04	-2.92E-04	5.74E-04	-2.76E-04	8.63E-07	8.64E-07	4.35E-06	-1.91E-05
Ox:2300, (3 m^3)	4.35E-04	-9.97E-04	4.24E-04	-1.04E-03	5.35E-05	2.53E-04	-4.45E-05	-2.16E-04
Ox:2300, (3 m^3), 10 m^3	3.01E-04	-9.56E-04	3.33E-04	-8.01E-04	8.63E-07	8.64E-07	-3.54E-05	-1.58E-04
Ox:700, (3 m^3)	8.74E-04	5.92E-04	8.23E-04	4.01E-04	5.35E-05	2.53E-04	1.09E-06	-6.50E-05
Ox:700, (3 m^3), 5.5 m^3	8.51E-04	8.62E-04	8.49E-04	9.00E-04	8.63E-07	8.64E-07	4.35E-06	-4.02E-05
Ox:700, (2 m^3), 4.5 m^3	8.35E-04	9.08E-04	8.32E-04	9.48E-04	8.63E-07	8.64E-07	4.35E-06	-4.18E-05
Total variation	**$3.01 \cdot 10^{-4} – 1.05 \cdot 10^{-3}$**	**$-9.97 \cdot 10^{-4} – 1.61 \cdot 10^{-3}$**						
Rewetting	$4.34 \cdot 10^{-4} – 1.05 \cdot 10^{-3}$	$-9.97 \cdot 10^{-4} – 1.45 \cdot 10^{-3}$						
Afforestation	$3.01 \cdot 10^{-4} – 9.48 \cdot 10^{-4}$	$-9.56 \cdot 10^{-4} – 1.61 \cdot 10^{-3}$						

11.4 Utilisation of old peat harvesting sites for energy peat production

In this chapter the results of the scenarios for the old peat harvesting sites are presented. In Figure 11.22 the accumulated emissions for the rewetting scenarios are given. There are only three different emission scenarios for CO_2 depending on the initial uptake/emissions. Since the re-wetted site will be a larger sink of CO_2 than the old harvesting site, there are decreasing trends for all three CO_2 emission scenarios. There is only one emission scenario for the N_2O emissions and those emissions are assumed to be of equal magnitude before and after the harvesting period.

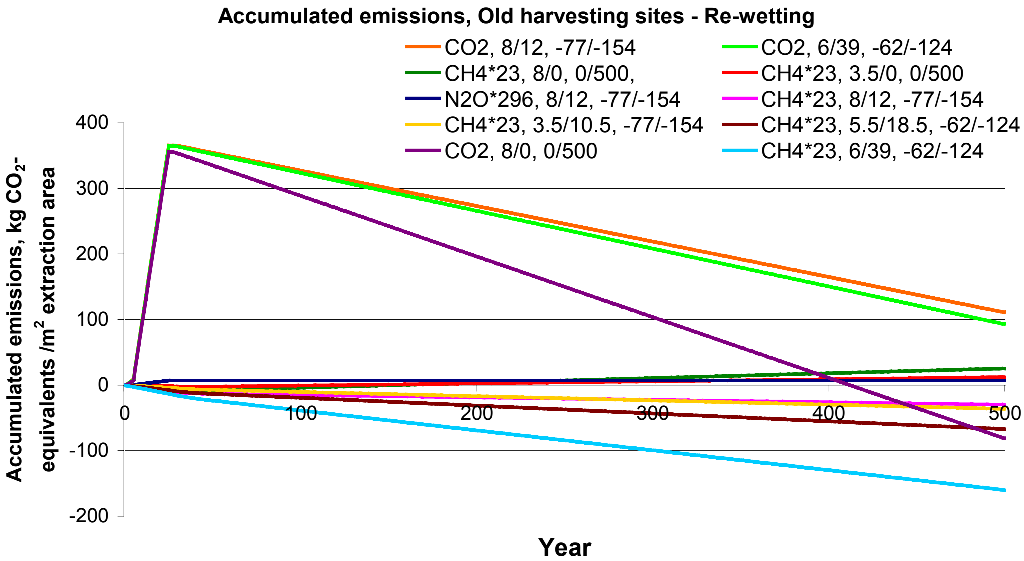


Figure 11.22 The accumulated emissions of CO_2, CH_4 and N_2O for the scenarios describing a sequence of old harvesting sites- peat harvesting – rewetting. As the legend indicates the methane emissions are multiplied by a factor of 23 and the nitrous oxide emissions are multiplied by a factor of 296 (these factors are the GWP_{100} factors for those gases). The first quota of the scenario names indicates the methane emissions at the unaffected and affected area respectively. The second quota of the scenario names indicates the corresponding value for CO_2. A negative value is a net uptake and a positive value is net emissions. Also see Table 10.1 for a closer description of the scenarios.

In Figure 11.23 and Figure 11.24 the instantaneous and accumulated radiative forcing for the re-wetting scenarios are presented. The results resemble those of the pristine mires. The scenarios with the lowest climate impact are those where it is assumed that the drainage is still effective and there is a loss of carbon by decomposition of the peat layer.

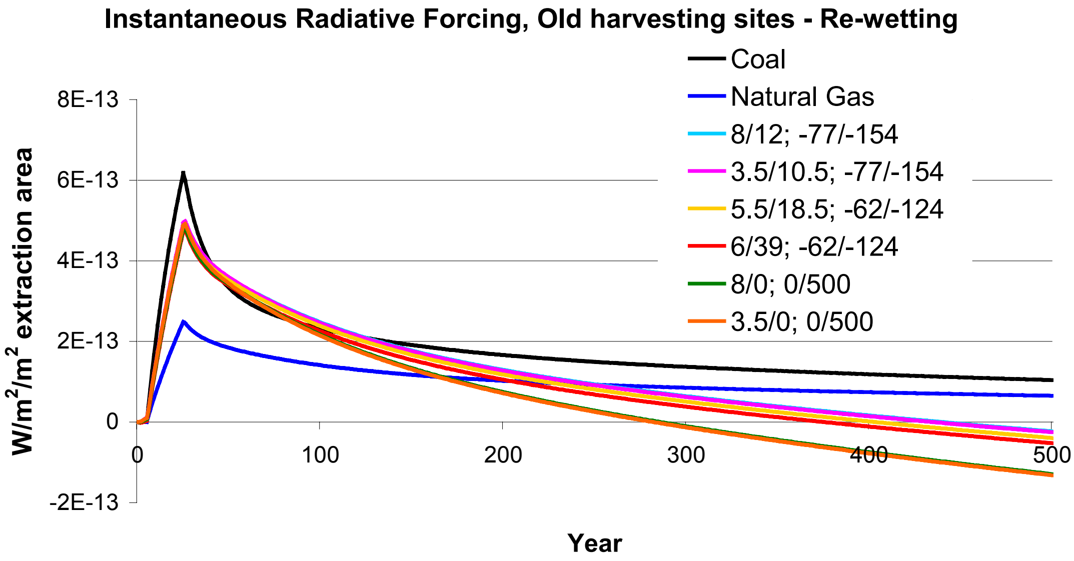


Figure 11.23 The instantaneous radiative forcing resulting from the rewetting scenarios of the old peat harvesting areas. The scenario names are the same as in the previous figure with the exception that each scenario here represents the effect of all three gases together.

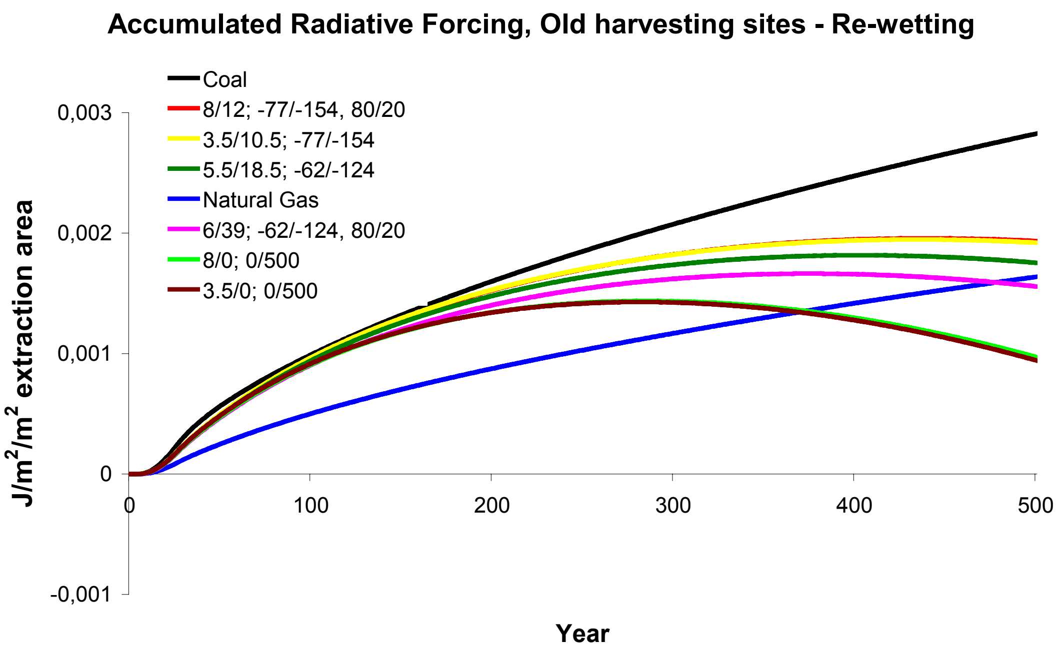


Figure 11.24. The total accumulated radiative forcing resulting from the rewetting scenarios of the old peat harvesting sites.

The results are all based on scenarios where we assumed that one fifth of the area has actually been harvested before. In Figure 11.28, at the end of this section, there are a few scenarios with different amounts of the mire area affected by harvesting.

In Figure 11.25 the accumulated emissions for the afforestation scenarios are given. Within each of the two groups the CO_2-emission-scenarios results are quite similar. Only the scenarios where the old harvesting sites are assumed to be net emitters of CO_2 (drainage still effective), the accumulated emissions level out on a significantly lower level than the other ones. There is only one emission scenario for the nitrous oxide emissions. There are six different emission scenarios for methane and since the afforested sites are assumed to have negligible methane emissions the trend for the accumulated emissions are all decreasing.

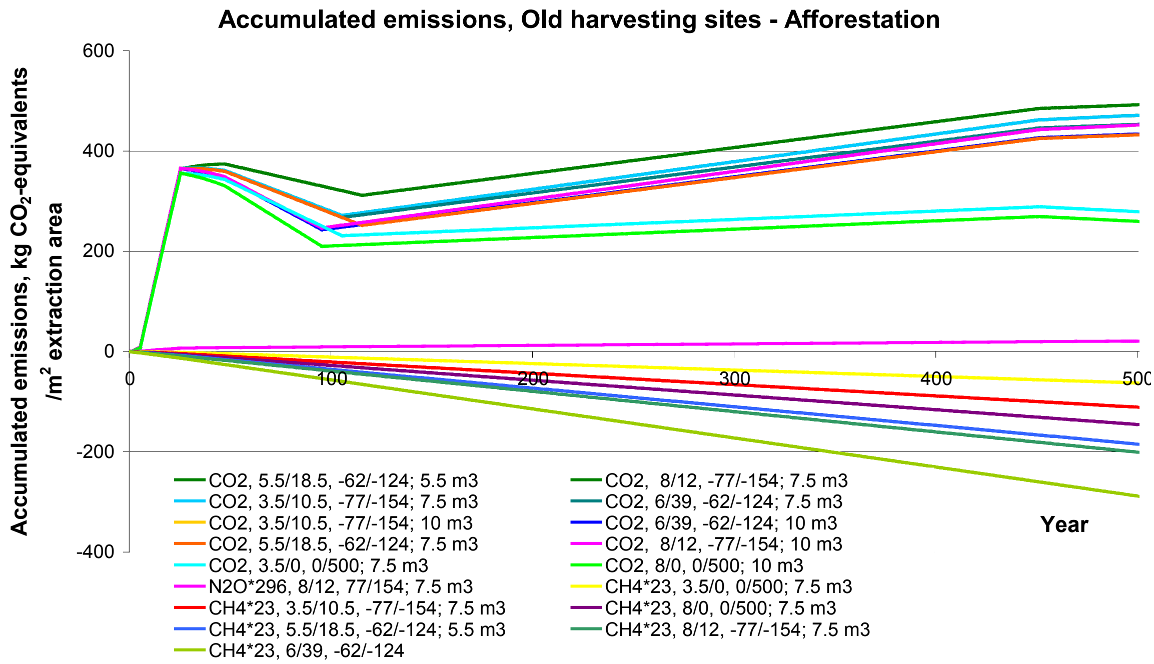


Figure 11.25 The accumulated emissions of CO_2, CH_4 and N_2O for the scenarios describing a sequence of old harvesting sites- peat harvesting – afforestation. The denotation of the scenarios is the same as in Figure 11.22 with the addition of the forest productivity at the after-treated sites given at the end.

In Figure 11.26 and Figure 11.27 the instantaneous and accumulated radiative forcing of the afforestation scenarios for the old harvesting sites are presented. As for the rewetting scenarios these results resemble those of the pristine mires. Again the scenarios resulting in the lowest climate impact are those where the drainage was assumed to still be effective and the site was loosing carbon by net peat oxidation.

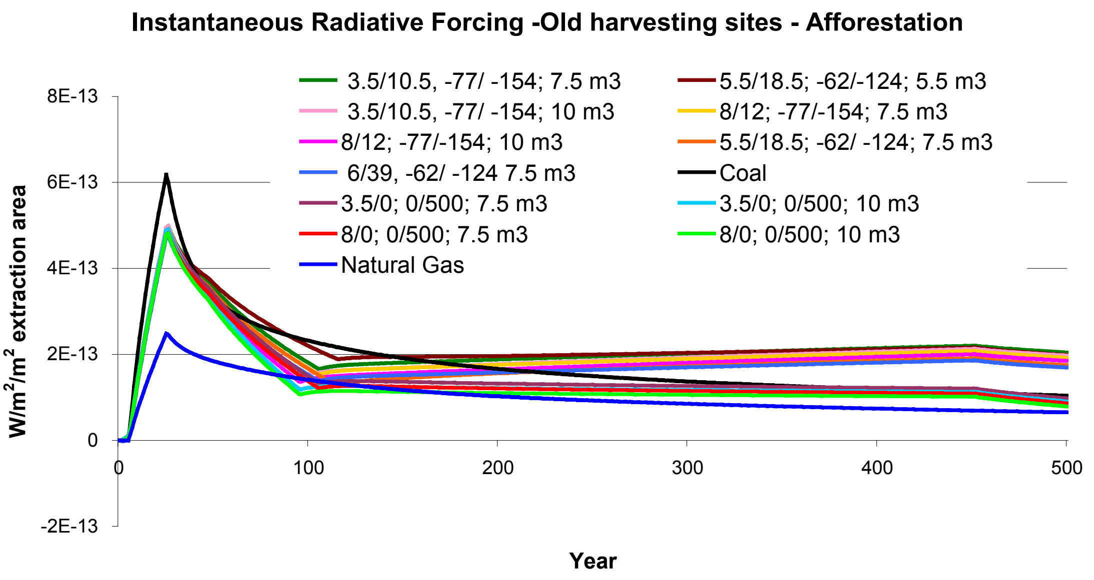


Figure 11.26. The instantaneous radiative forcing resulting from the peat-harvesting - afforestation scenarios of the old peat harvesting areas.

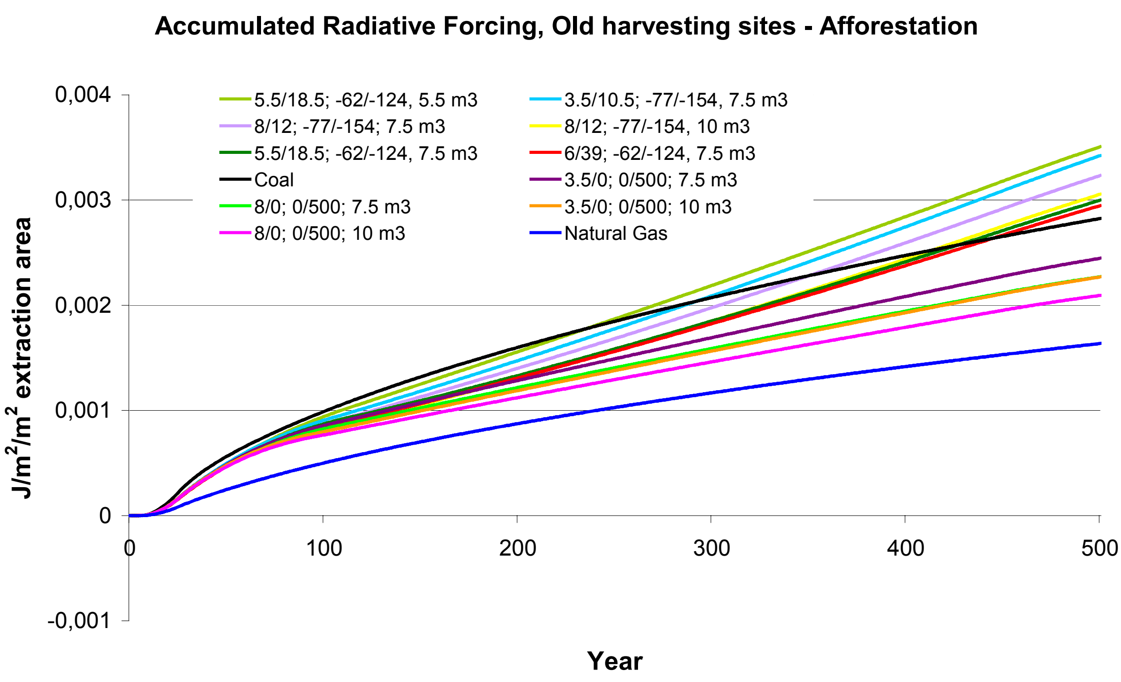


Figure 11.27. The total accumulated radiative forcing resulting from the peat-harvesting - afforestation scenarios of the old peat harvesting sites.

In Figure 11.28 the results of a few scenarios with different area affected is shown. The three uppermost scenarios (except for coal) all represents bogs where peat litter for livestock rearing have been extracted. The areas in those scenarios have been water-logged and hence the cut-away areas have become larger sources of methane and larger sinks of CO_2. Since bogs have relatively low methane emissions the effect of former harvesting is quite small. There are also three scenarios representing a low sedge fen with different portions of the area affected by former harvesting activities. In the fen case the effect of how much of the area that has been affected by former harvesting activities is greater. One of the reasons is that the increase in methane production at the fen site is much larger.

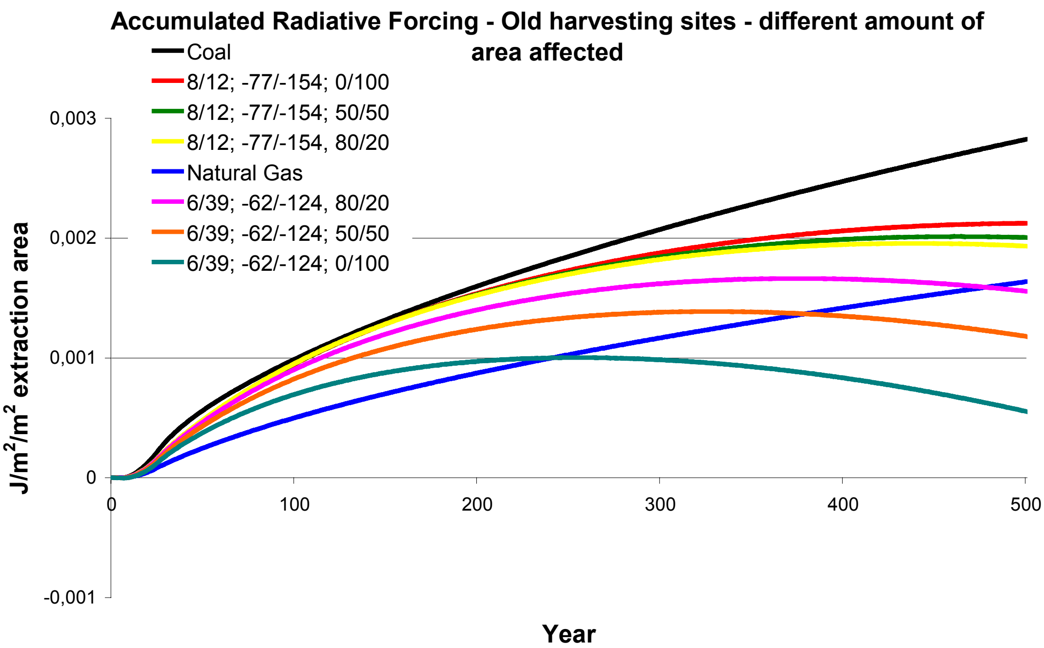


Figure 11.28. The impact of the assumption of how large portion of the area on the old peat harvesting site that has been affected by previous harvesting. The scenarios are named analogous to the other old harvesting site scenarios. The quota at the end of the scenario name indicates the portion of the area affected by the previous harvesting. 80/20 mean that 80% of the area was not directly affected by the previous harvesting activity and 20% was. The aftertreatment method is rewetting for all scenarios.

In Table 11.4 the numerical values of the accumulated radiative forcing of the different scenarios is given for 100 and 300 years respectively.

Table 11.4 Accumulated Radiative Forcing for old harvesting sites scenarios. [$J/m^2/m^2$extraction area]

Land-use	Total Accumulated Radiative Forcing		Accumulated Radiative Forcing					
	t = 100	t=300	CO_2, t=100	CO_2, t= 300	CH_4, t=100	CH_4, t = 300	N_2O, t= 100	N_2O, t= 300
8/12, -77/-154,	9.55E-04	1.82E-03	9.73E-04	1.84E-03	-3.16E-05	-4.76E-05	1.71E-05	2.98E-05
8/12; -77/-154, (7.5 m^3)	8.72E-04	1.98E-03	9.28E-04	2.18E-03	-7.36E-05	-2.50E-04	2.03E-05	5.45E-05
8/12; -77/-154, (10 m^3)	8.13E-04	1.85E-03	8.69E-04	2.05E-03	-7.36E-05	-2.50E-04	2.03E-05	5.45E-05
3.5/10.5, -77/-154	9.65E-04	1.82E-03	9.73E-04	1.84E-03	-2.09E-05	-4.89E-05	1.71E-05	2.98E-05
3.5/10.5; -77/-154, (7.5 m^3)	9.06E-04	2.09E-03	9.28E-04	2.18E-03	-3.93E-05	-1.37E-04	2.03E-05	5.45E-05
3.5/10.5; -77/-154, (10 m^3)	8.47E-04	1.96E-03	8.69E-04	2.05E-03	-3.93E-05	-1.37E-04	2.03E-05	5.45E-05
6/39, -62/-124	9.05E-04	1.62E-03	9.66E-04	1.80E-03	-7.55E-05	-2.08E-04	1.71E-05	2.98E-05
6/39; -62/-124, (7.5 m^3)	8.33E-04	1.83E-03	9.22E-04	2.13E-03	-1.07E-04	-3.59E-04	2.03E-05	5.45E-05
6/39; -62/-124, (10 m^3)	7.73E-04	1.70E-03	8.62E-04	2.01E-03	-1.07E-04	-3.59E-04	2.03E-05	5.45E-05
5.5/18.5, -62/-124	9.41E-04	1.74E-03	9.66E-04	1.80E-03	-3.86E-05	-9.06E-05	1.71E-05	2.98E-05
5.5/18.5; -62/-124, (5.5 m^3)	9.42E-04	2.19E-03	9.92E-04	2.37E-03	-6.75E-05	-2.30E-04	2.03E-05	5.45E-05
5.5/18.5; -62/-124, (7.5 m^3)	8.72E-04	1.85E-03	9.22E-04	2.03E-03	-6.75E-05	-2.30E-04	2.03E-05	5.45E-05
3.5/0; 0/500, 80/20	9.16E-04	1.42E-03	9.05E-04	1.38E-03	-2.42E-06	1.16E-05	1.71E-05	2.98E-05
3.5/0; 0/500; (7.5 m^3)	8.57E-04	1.69E-03	8.60E-04	1.72E-03	-2.08E-05	-7.68E-05	2.03E-05	5.45E-05
3.5/0; 0/500; (10 m^3)	7.98E-04	1.57E-03	8.01E-04	1.59E-03	-2.08E-05	-7.68E-05	2.03E-05	5.45E-05
8/0; 0/500, 80/20	9.08E-04	1.43E-03	9.05E-04	1.38E-03	-1.04E-05	2.15E-05	1.71E-05	2.98E-05
8/0; 0/500; (7.5 m^3)	8.26E-04	1.59E-03	8.60E-04	1.72E-03	-5.25E-05	-1.81E-04	2.03E-05	5.45E-05
8/0; 0/500; (10 m^3)	7.67E-04	1.46E-03	8.01E-04	1.59E-03	-5.25E-05	-1.81E-04	2.03E-05	5.45E-05
Total variation	**$7.73 \cdot 10^{-4} – 9.65 \cdot 10^{-4}$**	**$1.42 \cdot 10^{-3} – 2.19 \cdot 10^{-3}$**						
Rewetting	$9.05 \cdot 10^{-4} – 9.65 \cdot 10^{-4}$	$1.42 \cdot 10^{-3} – 1.82 \cdot 10^{-3}$						
Afforestation	$7.73 \cdot 10^{-4} – 9.42 \cdot 10^{-4}$	$1.46 \cdot 10^{-3} – 2.19 \cdot 10^{-3}$						

12 Results - The total climate impact of the current peat utilisation in Sweden

By contacting energy peat producers all over Sweden, information on former land-use and vegetation of active peat production sites was compiled. The compiled information covers approximately 55% of the production of energy peat in Sweden. Table 12.1 below show how much of the production that the harvesting sites with known history (land-use or vegetation cover before harvesting) stands for.

Table 12.1. Production at harvesting sites for which information on land-use and vegetation have been received.

Region	Average production 2000 – 2003 [MWh]	Total production in region [MWh]	% of total production
Norrland	624 780	1 241 856	50%
Svealand	290 753	468 288	62%
Götaland	407 605	645 545	63 %
Sverige	1 323 138	2 355 689	56 %

Each of the harvesting sites were described by one of the scenarios in the previous section. If the mire was described as a pristine mire before the start of harvesting it could e.g. be classified as a tall sedge mire situated in region 3-I and then scenario four or five in Table 7.6 was used. In many cases the mires could be classified as a mixture of mire types (or land-use). In those cases the calculation was done by weighting the different scenarios and assuming for example 25% of the mire to be pristine and 75% of the mire to be affected by forest drainage. Table 12.2 summarises the distribution of the harvesting sites with known land use history between the four peatland types as defined in this study.

Table 12.2. The distribution of the harvesting sites with known land-use history.

Mire type/land-use	Production [MWh]	% of harvesting sites with known land-use history
Pristine mires	369 501	28
Agricultural land	111 336	8
Drained forest	280 374	21
Old harvesting sites	561 928	42

Two different calculations were made regarding the after-treatment procedure, one assuming all harvesting sites being after-treated by afforestation and one by assuming all harvesting sites being after-treated by rewetting. The results of the calculations are shown in Figure 12.1 below.

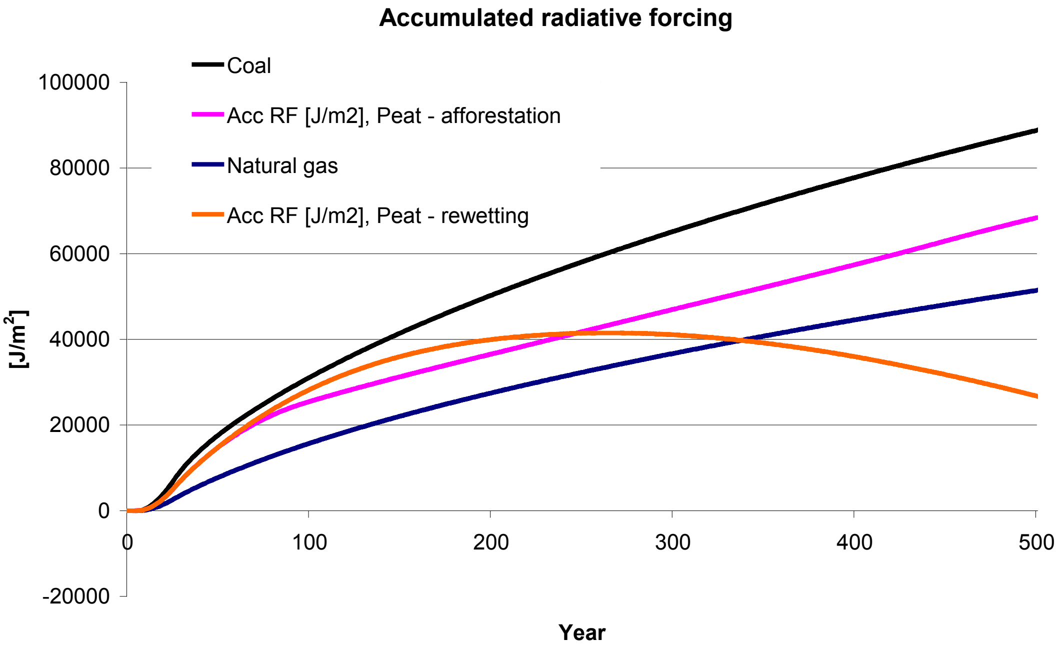


Figure 12.1. Estimate of the radiative forcing due to 20 years of utilisation of energy peat (from sites with known land-use history) in Sweden, at a level corresponding to 55% of the current total yearly production (i.e. 1.3 MWh/a). Two scenarios were made one with all sites being restored by afforestation and one with all sites being restored by re-wetting.

It should be noted that all uncertainties described in earlier sections concerning emissions and uptake of gases are contained also in these calculations. The figure shows that in the long term perspective it is better to return the harvested peatland to a wetland since this ecosystem has a long-term ability to act as a carbon sink. However, how large that sink will be and for how long it will last is uncertain. The simulations also reveal that in the short time perspective (<100 years) restoration by afforestation will result in a smaller climate impact.

We also made calculations on the accumulated radiative forcing caused by a continuous utilisation of energy peat, assuming the same type of peatlands to be used as today. The calculations show that the continuous utilisation of energy peat results in the accumulated radiative forcing being somewhere between the corresponding value for coal and natural gas. In Figure 12.2 it can be seen that with time the accumulated radiative forcing of the peat scenarios will be declining compared to the coal scenario.

We also made a calculation of the accumulated radiative forcing due to continuous peat harvesting at peatlands drained for forestry. Two of the previous presented scenarios were used, i.e. the scenarios with an initial oxidation rate of the peat layer of 900 g CO_2/m^2. The result is shown in Figure 12.3. Comparing Figure 12.2 and Figure 12.3 it can be seen that using peatlands that results in smaller climate impacts will have a long-term effect.

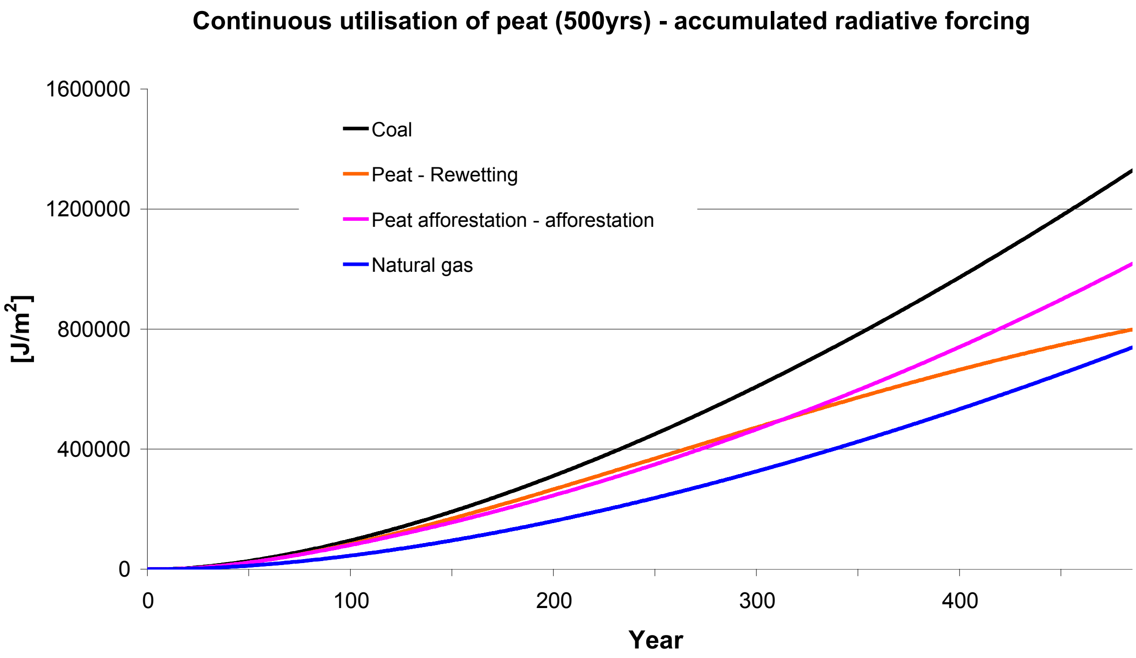


Figure 12.2. The accumulated radiative forcing caused by the continuous utilisation of Swedish energy peat at current known conditions (~1.3 MWh/a corresponds to 55% of current energy peat production).

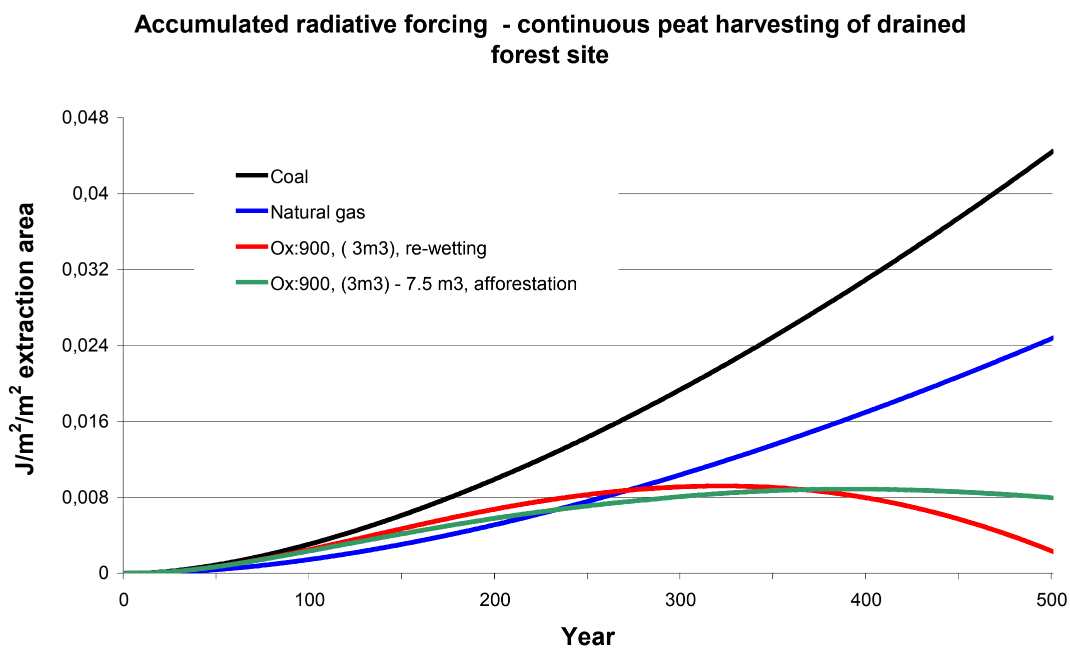


Figure 12.3 The accumulated radiative forcing due to 300 years of energy peat harvesting at peatlands previously drained for forestry. The scenario used is one of the scenarios described in the section for peatlands drained for forestry and both the re-wetting and afforestation scenarios are shown.

13 Discussion

In this study we have analysed the climate impact of a large number of scenarios related to the use of peatlands for energy in Sweden. Below we discuss the results and uncertainties for the different land-use categories and aftertreatment methodologies.

Pristine mires

For the pristine mire – rewetting scenarios the climate impact is during the first 200 years very similar to the climate impact estimated for coal. The scenarios for pristine mire - afforestation gave during the first 200 years a smaller climate impact than the pristine mire-re-wetting scenarios, at least in those cases where larger amounts of methane emissions were avoided (i.e. the pristine mire had large methane emissions) and the forest productivity was good. It is reasonable to assume that in general it will be possible to achieve good post-harvesting forest productivity by using fertilisers such as wood-ash. If the methane emissions at the re-wetted cut-away area could be kept below the level of the initial mire, as in the scenario in Figure 11.3, the radiative forcing of the peat scenarios would be significantly lower. In all other scenarios we have assumed that the methane emissions at the re-wetted sites will rise to the original value of the pristine mires.

Another factor influencing the outcome of the pristine mire scenarios is the assumed CO_2 uptake in the pristine mire. We have used the long-time averages, which probably are over-estimates. Lower values would make the reference scenarios worse from a greenhouse gas emission perspective, resulting in lower values of climate impact for the peat scenarios.

It is important to remember that this study was performed in order to investigate the climate impact of peat utilisation and we have therefore taken into account the carbon uptake by the growing forest during the first rotation only. From a land use perspective it is still possible (and very likely) that the land will be used for forest production during many rotations to come, but in order to calculate the climate impact of the long-term forest management, one will have to consider the use of the forest biomass (i.e. timber, biofuels, pulp etc.) and that was not within the scope of this study.

Agricultural peatlands

All agricultural peatland scenarios resulted in considerably lower climate impact than both coal and natural gas within a relatively short time period of 50 – 150 years. The reason is that the emissions of carbon dioxide and nitrous oxide from the reference scenario, i.e. present land-use of cultivated peatlands, are high. Very high peat oxidation rates are especially connected to cultivation of cereals and row crops, and these are reduced after removing the peat. The emissions of nitrous oxide (which are relatively high at all the organic agricultural soils) may remain high also after peat harvesting, at least at the surrounding area (von Arnold 2004). Since peat harvesting from agricultural peatlands result in a lower climate impact it seem reasonable to use such areas rather than pristine mires. In Sweden about 600 000 hectares of peatland has been drained for agriculture (Hånell, 1990). Today about 250 000 hectares are still in use for agricultural purposes (Statistics Sweden

1998) and the rest of the organic drained soils have either been afforested or lost by oxidation. However, the peat depths at those soils are not known. Due to fast oxidation, both during and after cultivation, the peat layer has been strongly affected. Therefore, without knowing the peat depth at those soils one can not estimate their potential energy peat production.

Afforested agricultural peatlands

Peatlands drained for agriculture but now afforested were not included in this study. However, it might still be of interest to investigate the climate impact resulting from peat harvesting from such areas. Studies made in for example Finland show that afforested organic soils (soils that were once used for agriculture but now have been afforested, the peat has not been removed) can be large sources of nitrous oxide emissions for a very long time period after the afforestation. Maljanen et al (2004) concluded that some afforested organic soils emitted N_2O at higher rate than cultivated organic soils, even 30 years after afforestation. Also investigations in Sweden imply that there might be considerable areas of former agricultural land, now afforested (peat not removed), that emit large amounts of greenhouse gases (von Arnold 2004). Hence using afforested former agricultural peatlands for peat harvesting might also give lower climate impacts than using pristine mires.

Forests on drained peat soils (low productive)

The uncertainties connected to the greenhouse gas balances at this type of peatlands are still considerable. Especially concerning the CO_2 net-balance and the determination of whether the system is a net source or a net sink of CO_2. Among the scenarios in this study there are both cases where the forest is a net source and a net sink of CO_2. In those cases the forest is a small net sink of CO_2, the calculated climate impact is close to the climate impact of coal, at least for a time period of 100 – 150 years. Also in those cases where the forest was assumed to be a small net source of CO_2, the calculated radiative forcing is close to the corresponding value of coal. Exceptions are scenarios where considerably higher forest productivity was achieved after the end of the harvesting.

Some of the scenarios made for forests on drained peat soils result in a considerably lower radiative forcing and after 100 – 200 years they are lower than natural gas. In those scenarios the originally drained peatland forests are assumed to be quite large sources of CO_2. Such large values of net CO_2 losses have not been reported from field measurements and they are rather theoretical estimates for sites with low productivity and high rates of oxidation. Von Arnold (2004) suggests that poorly drained sites are net sinks since the uptake by the growing forest compensates for the decomposition of the under-laying peat. More well drained sites might be net sources since the uptake of CO_2 in the growing forest can not compensate for the decomposition of the under laying peat. The assumptions made concerning the CO_2 net-balance will have great impact on the results. The radiative forcing from sites that are net sources of CO_2 is generally higher than from sites that are net sinks. Because the CO_2 net balance is of such great importance our results that originally were said to be valid for low-productive sites in fact could be valid also for medium or high-productive sites with similar net CO_2 balances. A high productive site with a high rate of oxidation of the under-laying peat layer might also have a net CO_2 balance similar to those used in our scenarios. Since we have assumed a significantly higher productivity after the peat harvesting at the low productive sites (that could be compared to medium or high productive sites) the scenarios might be representative also for sites of other productivity.

Old peat harvesting sites

The climate impact of those scenarios resemble the climate impact of the pristine mire scenarios. The main reason for that is our assumption that the former harvesting activity affected only 20% of the extraction area. In those scenarios where the affected area was larger, it is clear that the climate impact is smaller (see Figure 11.28) due to the reference scenario having higher emissions of greenhouse gases.

We do not suggest that the average affected area of former harvesting sites is either 20%, 50% or 100%, but we want to point out the importance of this factor. This issue will be of importance when considering an individual case.

According to D. Fredriksson (personal communication, 2004) it is reasonable to assume that the affected area at old harvesting areas, where peat litter for livestock rearing has been harvested, is considerably larger then 20%. More likely, at 50% of the area the uppermost peat layer has been removed whereas the other 50% of the area has been used for drying and hence has been affected by drainage.

After-treatment

The after-treatment is of great importance to the climate impact of energy peat utilisation. Afforestation will result in a positive effect in a shorter time perspective, while rewetting and creation of new wetlands will have a potentially positive effect on the greenhouse gas balance in the long run.

It should be noted that the uncertainty connected to the assumptions of the values of the greenhouse gas balances at a re-wetted site, especially the CO_2 balance but also how fast the methane emissions recover, is great. Only a few studies with actual measurements have been made and they only represent the initial stage of the development. There is a need for long-term studies of these balances at different types of harvested peatlands. Such studies could also help us evaluate the possibilities for regulating the greenhouse gas balances in a favourable direction. Is it possible to speed up the succession of wetlands, to faster reach a bog-like stage where fen species who increase the methane emissions are less abundant or absent but where the CO_2 sequestration still is at a high level? What management is required and for how long, etc. If the methane emissions could be regulated and could be kept below the level of the initial mire the radiative forcing of the peat scenarios would be significantly lower (see Figure 11.3).

In the cases where afforestation is used as after-treatment method it has been assumed that the accumulation of CO_2-C in the soil also will be limited to the first rotation. This assumption is quite uncertain since there are no studies on the carbon dynamics of the soil on an afforested cut-away peatland. If there is a potential to further increase the soil carbon then it would however be dependent on the future forest management and that is not within the scope of this study.

In this study the CO_2 uptake in the growing forest have only been considered during one rotation. The reason is that we wanted to investigate the climate impact of peat utilisation and not the effect of forestry. However, if one would consider the cutting and harvesting of further forest rotations and also assume that the harvested biomass could be used for energy production replacing fossil fuels the radiative forcing scenarios would look significantly different, resulting in smaller climate impacts.

In Olsson et al (2002) it is concluded that if peatlands are to be harvested it is very important to make the extraction complete both vertically and horizontally. Depending on how complete the harvesting has been, different aftertreatment methodologies are preferable. According to Olsson et al (2002) the best after-treatment, after removing all peat, is afforestation, since this alternative will give a long lasting decrease of greenhouse gas emissions. This conclusion is made assuming continuous forest management on the after-treated area. According to Olsson et al (2002) rewetting a site can initially mean a sink of greenhouse gas emissions that in a longer perspective probably will change to a source. As mentioned earlier little is known of the long term development of the methane and carbon dioxide balances of newly re-wetted areas. Hence, how long it will take until a re-wetted area becomes a net source is very uncertain.

The climate impact of current peat utilisation in Sweden

The calculations of the climate impact of the current use of energy peat were made by classifying currently used harvesting areas into the four categories investigated in this study. The information available for this classification was sometimes poor but the relatively large sample of sites, it was based on harvesting areas corresponding to over 50% of the current production, will probably keep the uncertainty of the classification within reasonable limits. No investigation of intended or already started after-treatments was made. The two extreme cases with either only re-wetting or only afforestation were used. Probably a mixture of these two, or even other, after-treatments will be used in practice. Hence the calculated climate impact can only give an indication of what the actual value is.

Continuous utilisation of energy peat in Sweden

The scenarios of accumulated radiative forcing resulting of 500 years of continuous peat utilisation are based on the scenarios of the current utilisation. It was assumed that the same type of peatlands and the same amount of land would be required also in the future in order to produce the same amount of energy. The same uncertainties will then be associated to the continuous scenarios as for the current scenario, but the fact that the same assumptions were used concerning the area required and energy produced make them comparable.

General assumptions and uncertainties

The size of the surrounding area, i.e. the area outside the extraction area also affected by drainage will have some impact on the result. A large surrounding area will lead both to a larger amount of avoided methane emissions and a larger amount of CO_2 released due to decomposition during drainage or afforestation. The net effect will also depend on the assumed peat depth at the surrounding area. The assumption of the peat depth at the surrounding area is not based on any measurements but rather based on what has been assumed in previous studies and considered reasonable. This assumption will be of more importance in the case of afforestation than in the case of re-wetting after the peat harvesting since the remaining peat is assumed to oxidise. When the cut-away area is re-wetted the remaining peat layer is prevented from oxidation. If the peat depth at the surrounding area is shallower then what has been assumed in this study (half the peat depth of the extraction area), the peat scenarios will result in a smaller climate impact.

The peat depth at the extraction area will also have some impact on the result. If the peat layer is thinner than assumed in this study the, extractable energy per m^2 will be less. If peat harvesting will yield less energy per m^2 this will result in the relative amount of CO_2 emissions being somewhat higher (the relative emissions due to the combustion will be unaffected, the relative emissions caused by drainage will be higher and the lost CO_2 uptake will be relatively larger) and the relative amounts of methane emissions avoided being higher, when using pristine mires for energy peat harvesting. This will result in either a smaller or a larger climate impact per utilised amount of peat, depending on the absolute size of those effects. At peatlands already drained, the extraction of a thinner peat layer will mean the same relative amount of CO_2 emissions (if it is assumed that the combusted peat would have been oxidised if not harvested) but the relative effect of avoided emissions of nitrous oxide (at for example agricultural fields) will be higher. At sites with initially high emissions of nitrous oxide this will result in a relatively lower climate impact.

The CO_2 emission factor for combustion of peat used in this study is based on Nilsson (2004). The value of the emission factor depend on the water content and the value used is based on both estimated averages of water content given by producers and figures from Statistics Sweden. The N_2O emission factor for combustion of peat is dependent on the technology used. The value used in this study is based on Uppenberg (1999) where consideration to the currently used technology at the combustion plants in Sweden has been made. The same is true for the CH_4 emission factor.

The greenhouse gas balances of the four peatland types differ and are not equally well studied. The greenhouse gas balances of pristine mires are quite well studied and known, whereas data from drained forests are scarce and currently in focus for research. Organic soils have been studied to some extent but old and abandoned harvesting areas are poorly described in the literature.

Time is a very important factor in this study. Some of the more uncertain assumptions made, such as the assumption of CH_4 emissions and CO_2 uptake in a newly created wetland, are also assumed to be valid for a long time period. All scenarios have been calculated for a 500-year period. The values of both emissions and radiative forcing are more certain for the beginning of the time period and the uncertainty increases with time. It is important to be aware of this when looking at the results and it is also the reason why we have chosen the time period of 100 and 300 years respectively when presenting the numerical values in Table 11.1 - Table 11.4. 100 years is the time period recommended by the IPCC and 300 years is given as an indicative value for longer time perspectives. The 500-year values presented in the figures should be treated with care.

Comparison of results to other studies

In a Finnish study made by Savolainen et al (1994) the radiative forcing of the use of forest residues, peat from different types of peatlands and fossil fuels for energy production are compared. Their comparison has been performed with a methodology similar to the methodology used in this study. Savolainen et al (1994) concludes that in a 100-year perspective the use of coal or pristine mires for energy production will result in similar values of radiative forcing. Natural gas and cultivated peatlands (i.e. peatlands drained for agriculture) gave significantly lower values of radiative forcing but were comparable to each other. These results are similar to what we have found in this study.

Uppenberg et al (2001) have used the same methodology to determine the radiative forcing of the use of energy peat as we have in this study. In Uppenberg only pristine mires were investigated and the results show that within a 200 – 250 year period all energy peat scenarios result in a radiative forcing between the value for coal and natural gas. This is also in line with the results of this study.

14 Conclusions

The time horizon advised by IPCC for assessing the impact of land-use on green house gas emissions is 100 years. Independent of aftertreatment practises the current extraction and use of energy peat in Sweden results in a lower radiative forcing than coal but higher than natural gas if used for production of the same amount of heat or electricity. The calculated value for the radiative forcing of current peat utilisation for energy in a 100-year perspective ranges between 80-90% of the corresponding radiative forcing for coal and 165-180% of the corresponding value for natural gas. The corresponding values over a longer time period, i.e. 300 years, are 60-70% for coal and 110-130% for natural gas respectively.

An important conclusion from this study is that the initial land-use history and the after-treatment method of the peatlands has a major influence of the resulting radiative forcing caused by peat harvesting. The investigated types of peatlands and the radiative forcing from them indicate that there is a potential to reduce the current radiative forcing from the use of energy peat in Sweden by actively selecting harvesting sites. The radiative forcing over a 100-year period from peat utilisation using agricultural land ranges between negative values (potential net cooling effect) and 70% of the corresponding value for coal or 120% of natural gas. The radiative forcing over a 300-year period ranges between negative values (of considerable magnitude) and 20% of the corresponding value of coal or 34% of natural gas.

The simulated radiative forcing from drained forested peat soils used for energy peat production is quite diverse. The model results depend heavily on the assumed greenhouse gas balance of the forested drained peat soil. Even if most of the published studies indicate that drained and forested peatlands represent a greenhouse gas sink, there is still some uncertainty. The results of this study indicate that the radiative forcing caused by using drained forests for energy peat production ranges between 30-106% of the radiative forcing caused by using coal and 60-210% of the value of natural gas in a 100-year perspective. Over a 300-year period the radiative forcing will range between negative values (small –moderate) and 78% of coal or 137 % of natural gas. Assuming drained and forested peatlands being net greenhouse gas sink results in a less positive effect if such sites are used for energy peat production. If drained and forested peatlands represent a net source of CO_2 the use of energy peat from such sites are more favourable.

The radiative forcing caused by using pristine peatlands or old harvesting sites for energy peat production are in the same range as the radiative forcing caused by current production and utilisation of energy peat. There might be old harvesting areas with larger net greenhouse gas emissions than assumed in this study and using such sites would result in smaller values of radiative forcing. However, there is very little data on the greenhouse gas balances and other conditions of these sites.

Agricultural peatlands (organic soils) are currently large sources of greenhouse gases. By selecting agricultural peatlands (or abandoned agricultural peatlands) for energy peat harvesting there is a potential of reducing the radiative forcing of peat utilisation in Sweden. In order to determine the potential of using these types of peatlands an inventory of the abundance and availability of such areas is needed. Also afforested former agricultural land could be included.

It can further be concluded that the aftertreatment method used is the most important factor controlling the effect on radiative forcing from energy peat utilisation. There is a need of further research of the greenhouse gas balances at after-treated harvesting areas. Also the greenhouse gas balances at for example the drained forests and old harvesting sites should be investigated further.

There is a fundamental difference between the potential climate impact of energy peat utilisation and utilisation of fossil fuels. If re-wetting the harvested area, peat accumulation will start soon after the end of harvesting. The new wetland represents a potential long-term carbon sink. However re-wetting can also lead to large methane emissions fuelled by fresh organic carbon from the mire plants. Management of re-wetted sites will therefore be very important. If the harvested area instead is afforested, the growing forest will compensate for some of the CO_2 emissions, however after one rotation the net uptake by the forest will cease.

The results of the calculations of the radiative forcing from continuous utilisation of energy peat show a slower development than the shorter harvesting - combustion scenarios. Since new peat continuously is burnt, it will take longer time before the benefit of the avoided methane emissions at the initial mire and the larger uptake of carbon dioxide at the after-treated area will make an impact.. If the scenarios were to be calculated for a longer time period than the 500 years in this study the benefit of the created wetlands will be seen just as for the single scenarios in the previous chapters. However, already the scenarios showing 500 years of continuous peat harvesting are very speculative scenarios since the uncertainty of most factors increases with time. The scenarios describing the continuous utilisation of peat from previously drained and forested peatlands during 500 years could be compared to the corresponding 20-year utilisation - scenarios in Figure 11.18 and Figure 11.21. From that comparison it can be seen that the positive effect of the after-treatment is delayed due to the continuous burning of peat. It can also be concluded from the calculation of continuous utilisation of energy peat (500 years) from peatlands drained for forestry that harvesting at sites with larger emissions of greenhouse gases will give a significantly lower climate impact than both currently used peatlands and coal, and the effect will be seen sooner.

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IVL Svenska Miljöinstitutet AB

IVL Swedish Environmental Research Institute Ltd

P.O. Box 210 60, SE-100 31 Stockholm
Visit: Hälsingegatan 43, Stockholm
Tel:: +46 (0)8 598 563 00
Fax: +46 (0) 8 598 563 90

P.O. Box 5302, SE-400 14 Göteborg
Visit: Aschebergsgatan 44
Tel:: +46 (0)31 725 62 00
Fax: +46 (0)31 725 62 90

www.ivl.se