REPORT

Comparative review of variations in LCA results and peatland emissions from energy peat utilisation

Jonas Höglund Fredrik Martinsson
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Anna Jarnehammar
Head of Unit

Swedish Environmental Research Institute

IVL Swedish Environmental Research Institute

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Telephone +46 (0)8-598 563 00	

Author

Jonas Höglund Fredrik Martinsson

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Summary

Several studies using a life-cycle perspective of energy peat (Holmgren, Kirkinen et al. 2006; Kirkinen, Minkkinen et al. 2007; Hagberg and Kristina Holmgren 2008; Väisänen, Silvan et al. 2013) have come to different results depending on the choice of peatland, the production method and the after-treatment alternative etc. These studies also show that the climate impact of energy peat can be significantly reduced compared to fossil fuels such as coal, by applying different production methods, using certain peatland types for production and applying different after-treatment strategies. Based on the knowledge available, more is now known about the relationship between peat and climate and how it can be affected.

According to this study which is a review of existing studies on energy peat and climate impact, a life-cycle perspective is needed in order to understand the total emissions and uptakes that occur throughout the peat utilization chain. The results from these studies show, despite of great uncertainties in emission estimates, that the climate impact of energy peat utilisation can be significantly reduced compared to today's production by choosing drained peatlands with initially high greenhouse gas emissions for peat production. Combustion emissions are just one part of the total life-cycle emissions.

Keyword

Peat, energy, climate impact, life-cycle analysis, emission factor

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Executive summary

According to IPCC (Intergovernmental Panel on Climate Change) peat is placed in its own class between fossil fuels and biofuels. Emissions from peat combustion are today treated in the same way as combustion of fossil fuels in the national reporting of greenhouse gases under the Climate Convention. The carbon dioxide emission factor for energy peat is 106 g CO_2/MJ.

Green electricity certificates are granted in Sweden to power produces using peat in the power production. The same producers must present emission allowances according to the EU-ETS (EU Emission Trading Scheme) for the carbon dioxide emissions associated with peat combustion. Consequently, energy peat competitiveness will depend on the price development of the EUAs (EU ETS emission allowances).

Previous research on energy peat and its climate effects has primarily studied different options for developing a peat production and utilisation which results in lower emissions of greenhouse gases. The studies considering the life cycle of energy peat utilisation have shown that the climate impact of energy peat is complex and more complicated than just considering the emissions at the combustion stage of peat. Before the combustion of peat, uptake and emissions of greenhouse gases are occurring at the peatland before, during and after peat extraction. These emissions will have an influence on the final climate impact from the peat utilisation chain which gives a more comprehensive picture of the total climate impact. The results from these studies show, despite of great uncertainties in emission estimates, that the climate impact of energy peat utilisation can be significantly reduced compared to today's production by choosing drained peatlands with initially high greenhouse gas emissions for peat production. The effect of using a life-cycle (LCA) perspective compared to only considering the emission at the combustion stage will therefore affect the total climate impact of energy peat.

Several studies using a life-cycle perspective of energy peat (Holmgren, Kirkinen et al. 2006; Kirkinen, Minkkinen et al. 2007; Hagberg and Kristina Holmgren 2008; Väisänen, Silvan et al. 2013) have come to different results depending on the choice of peatland, the production method and the after-treatment alternative etc. These studies also show that the climate impact of energy peat can be significantly reduced compared to fossil fuels such as coal, by applying different production methods, using certain peatland types for production and applying different after-treatment strategies. Based on the knowledge available, more is now known about the relationship between peat and climate and how it can be affected.

In order to make future production of peat better from a climate perspective, there is a need to compile current knowledge from existing LCA-studies and to assess how the choice of peatland, different production methods, and after-treatment strategies applied will affect the climate impact from energy peat compared to present situation. The aim of this study was to review and compare the results from previous LCA-studies in order to show variations between studies and to illustrate how peat production can be developed to minimize the climate impact of energy peat. The methods for performing life-cycle analyses have been developed in previous studies and made possible more accurate assessments of the climate impact of energy peat.

The review was done by:

- Summarizing emissions from the peat utilization chain from the start of peat extraction activities to the after-treatment phase. After-treatment options considered include afforestation and rewetting.
- Compiling LCA-results from previous studies in order to show variations in climate impact.
- Compare the results and discuss reasons for the differences in results.

The study shows that the climate impact from the combustion of energy peat over time can be compensated by after-treatment of the extracted area. This effect is most evident for high emitting peatlands (i.e. cultivated peatlands) but the effect can also be seen for other types of organic soils, such as forestry drained sites.
Figure 1 shows the climate impact from pristine peatland, forestry-drained peatland and cultivated peatlands over a 100 year perspective. As can be seen in the figure the climate impact from energy peat utilization has the potential to result in lower climate impact than coal in a 100 year perspective.

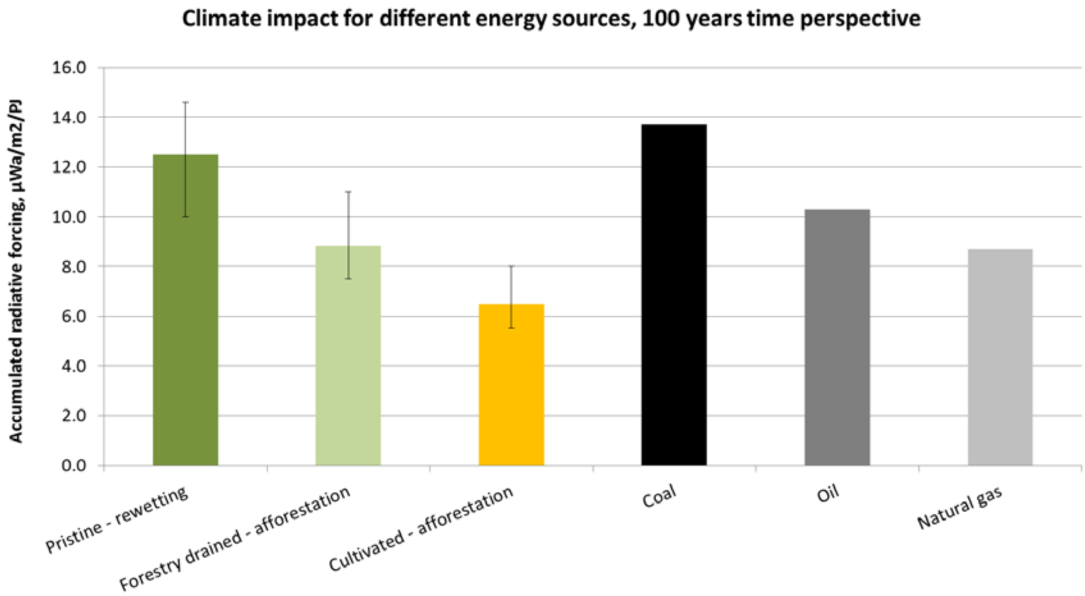

Figure 1. Summarized climate impact (accumulated radiative forcing) after 100 years for different energy peat utilization chains and fossil fuels. Three peatland scenarios are presented and compared with the climate impact from coal, oil and natural gas. The results show that the climate impact from peat utilization can be lower than coal in 100 years.

The following factors are the most important for the climate impact of energy peat production and utilization:

- The initial peatland type
  By extracting energy peat from agricultural peatlands the climate impact of energy peat can be lowered 33-65 % compared to coal utilization in a 100 year perspective. For forestry-drained sites the reduction potential is up to 35 % compared to the coal utilization scenario, based on existing research. In other words, forestry-

drained peatlands can lower the climate impact of energy peat, however not to the same extent as with agricultural peatland.

- After-treatment strategy

  Both afforestation and rewetting have potential to turn a peatland from a net source to a net sink of greenhouse gases after extraction has ceased; generally afforestation will decrease the climate impact in a shorter time span as compared to rewetting. After-treatment should be started as soon as possible. Which after-treatment alternative that is most suitable is dependent on the characteristics of the particular site in question.
- LCA methodology

  Available LCA-studies make different assumptions on emissions from different stages of the peat utilization chains. This is one reason why the results of the studies differ. The differences are mainly related to assumptions regarding emissions from the area surrounding the extraction site, emissions from the residual peat layer, carbon uptake in growing forest and emission factors for coal and peat. Existing methodologies for peat LCA should be further developed.

The time perspective from which the results are evaluated is of major importance for the results. The combustion emissions will dominate the emissions up to 100 years. If a longer time perspective is considered combustion emissions will over time be compensated for. Over long time spans the utilization of high-emitting peatlands will eventually show a positive climate effect (higher uptake than emissions).

This study shows that combustion emissions are just one part of the total life-cycle, and that a life-cycle perspective is needed in order to understand the total emissions and uptakes that occur thorough the peat utilization chain.
The effects of co-combustion were not included in this study. Based on available research it seems clear that co-combustion of peat and wood-fuels can have positive effects such as lower maintenance of boilers and higher efficiency which in turn can lead to lower emissions.
In order to better understand the climate impact of energy peat there is a need for more research on how different peatland types can be evaluated from a climate point of view. Even with more knowledge there will still be uncertainties in emissions from peatlands, but the possibility to choose the most suitable areas for extraction would be better.
This report was funded by the European Peat and Growing Media Association (EPAGMA).

Contents

1 Abbreviations

CH_4	Methane
CO_2	Carbon dioxide
EU	European Union
GHG	Greenhouse gas
GPP	Gross primary production
GWP	Global warming potential
IPCC	Intergovernmental Panel for Climate Change
LCA	Life cycle analysis
N_2O	Nitrous oxide
NEE	Net ecosystem exchange

1.1 Glossary

Boreal zone	Ecosystems located in northern and sub Antarctic hemispheres.
Carbon balance	The difference between the amount of carbon sequestrated by the growing vegetation and released during autotrophic and heterotrophic respiration.
CO_{2eq}	The global warming potential of greenhouse gases compared to carbon dioxide.
Cut-away peatland	Peatland previously used for peat extraction where extraction has ceased.
$g\ CO_2\ m^{-2}\ a^{-1}$	Gram of CO_2 measured per square meter and year.
Milling method	Commonly used extraction method for peat where the surface layer of the peat field is broken into fragments behind agricultural tractors.
Minerotrophic	Peatland that receives water from streams or springs. Nutrient rich.
New production method	The peat is extracted with an excavator and spread out by a spreader.
Ombrotrophic	Peatland that is fed only by precipitation. Nutrient poor.
Pristine peatland/mire	Peatlands in a natural state not affected by human activities.
Residual peat	The peat layer that remains after extraction has ceased in a cut-away peatland.
Radiative forcing	A measurement of the warming of the climate. A positive radiative forcing has a warming impact on the climate and vice versa.
Stockpile	The peat produced during the summer is stored in the stockpiles for deliveries during the heating season.
$t\ C\ ha^{-1}\ a^{-1}$	Tonne of carbon measured per hectare and year
Temperate zone	Ecosystems located between the tropics and the polar regions.

1. Introduction

The climate impact of energy peat utilisation depends on a range of factors and is strongly dependent on the assumptions made throughout the utilisation chain. In recent years a number of studies have been conducted using life-cycle analysis (LCA) in order to estimate the climate impact of energy peat compared to other options such as coal. Most studies have been conducted based on measurements from Finnish and Swedish peatlands.
The total life cycle emissions from energy peat extraction and use are dependent on the production phase of the peat, the after-treatment option and the assumptions made in a particular LCA-study.
The three most important greenhouse gases are Carbon dioxide (CO_2), Methane (CH_4) and Nitrous Oxide (N_2O). Both CH_4 and N_2O are more efficient greenhouse gases than CO_2, having a global warming potential of 25 and 298 times that of CO_2 over a 100-year time horizon, respectively (IPCC 2007). Peatland ecosystems can act either as sinks or sources of CO_2 depending on the rates of photosynthesis and respiration. N_2O is produced mainly by microbial processes whilst CH_4 is formed by anaerobic processes (Maljanen 2010).
In general, natural undrained peatlands are sinks for CO_2 (growing vegetation sequester carbon from the atmosphere) and sources of CH_4 (through anaerobic processes in the wet peat soil). N_2O emissions from undrained peatland sites are typically small or absent, but variations can be seen also here. On the other hand, agricultural peat soils are net sources of both CO_2 and N_2O, and sinks for CH_4 (Holmgren, Alm et al. 2010).
In boreal and temperate zones forestry-drained peatlands in general might be sinks for CO_2 since the carbon sequestration of the tree stand exceeds the peat decomposition rate. On average forestry-drained peatlands are small sources for CH_4 and N_2O (Holmgren, Kirkinen et al. 2006; Hagberg and Holmgren 2008; Maljanen 2010; Holmgren, Alm et al. 2011)
As mentioned earlier, emissions from peatlands varies depending on a range of factors. The most important parameters determining emissions from a particular peatland is the nutrient status and the climatic conditions (summer season length, precipitation etc.). In order to scientifically classify peatlands they are often analysed depending on their nutrient status and their climatographic location (boreal or temperate), a distinction which is also made in this report.
This report is a review study of emission fluxes reported in scientific literature for peatland soils in primarily boreal climatic zones. The aim of this study was to review and compare the results from previous LCA-studies in order to show the variation between studies and to illustrate how peat production can be developed to minimize the climate impact of energy peat. The report is based on an initiative from the European Peat and Growing Media Association (EPAGMA) that wanted a science based background on how system boundaries and assumptions made in existing life-cycle analyses on energy peat affect the results of final climate impact and the potentials in reducing these impacts by altering the production chain. The focus is peatlands in Finland, Sweden, Estonia and Ireland and the report is based on existing scientific literature.

2 Method

The geographical focus in this report is on the boreal biogeographic area. This includes among other parts most of Sweden, Finland and Estonia, Latvia and also large parts of the taiga in Russia. Boreal areas are also found in Canada and North America.

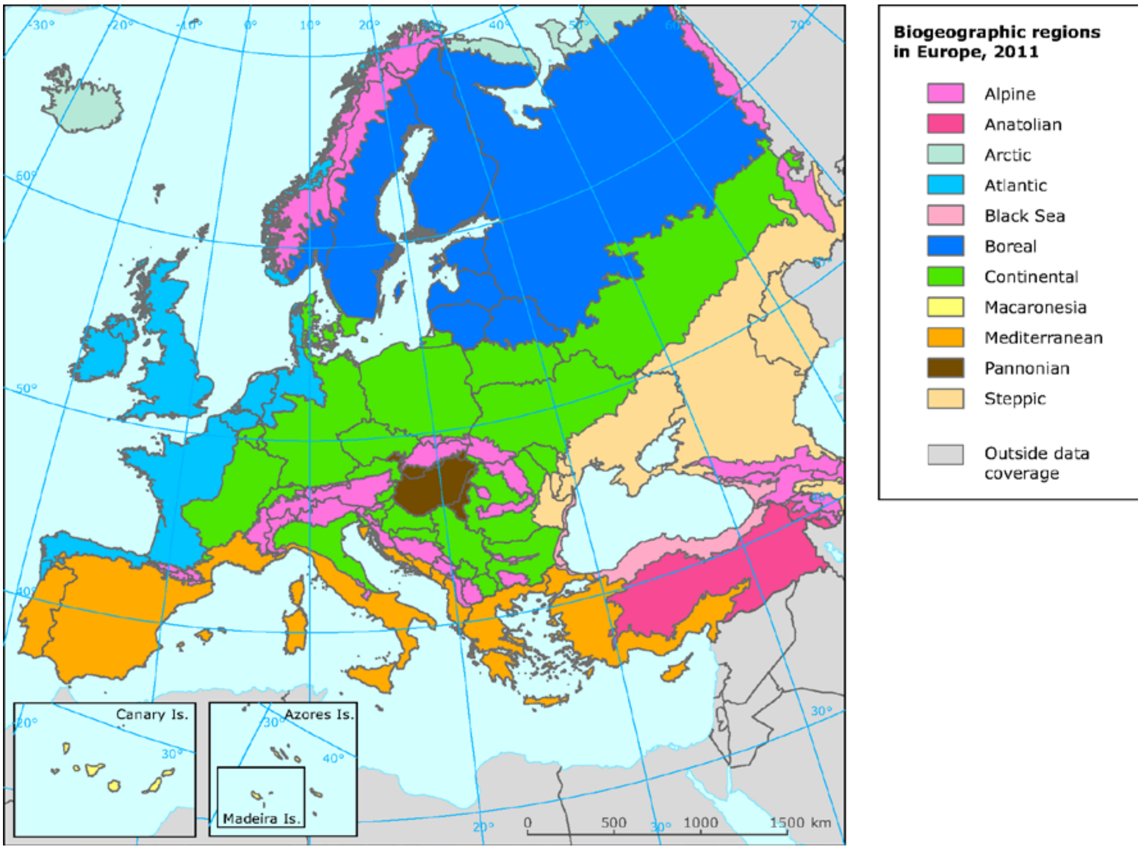

Figure 2: Biogeographic regions in Europe (EEA 2012)

The report also includes data sources from Ireland. One of the motives for this is the relative high level of land covered by peatland in Ireland (Figure 3 and Figure 17).

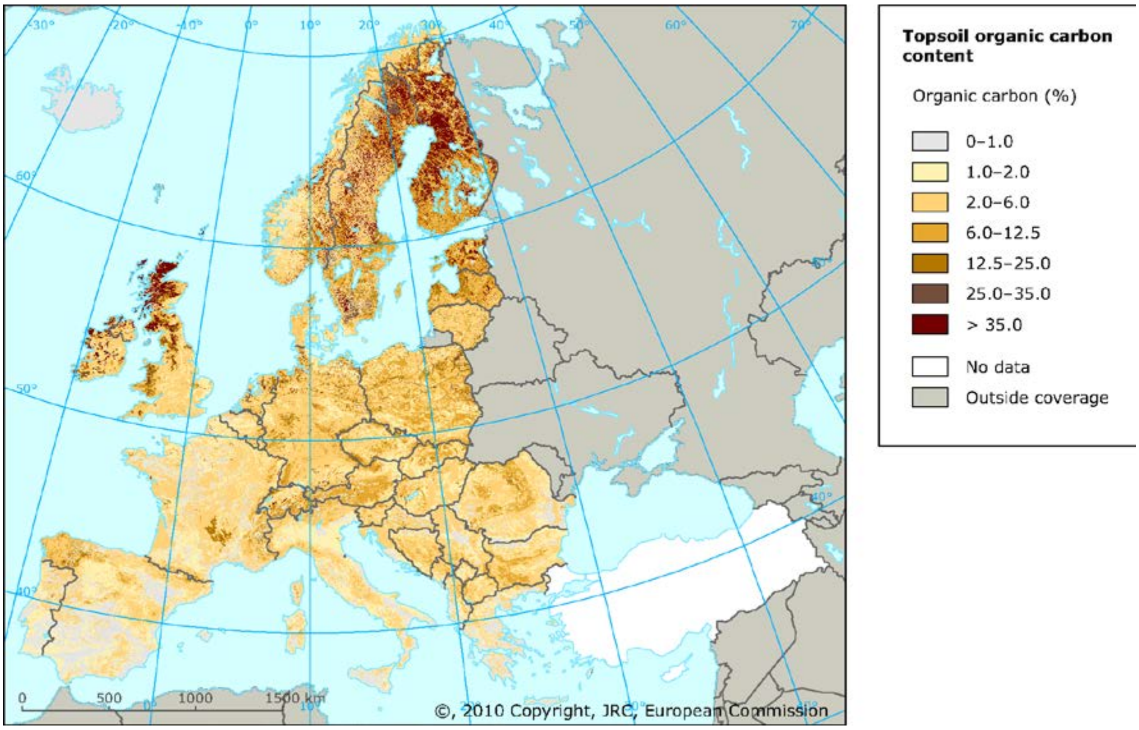

Figure 3: Topsoil organic carbon content (EEA 2010)

The land use is divided into a set of different management regimes.

- *Pristine/undisturbed mire and wetlands.* The water table has not been altered. In many countries the areas of natural mires and wetlands have been considerably reduced during the last 100 years (for Sweden see for example Naturvårdsverket 2012). In recent years attention to preserve and rehabilitate wetlands has been increased.
- *Forestry on peatlands.* In most cases the water table has been lowered as these lands are naturally wet. Forestry on peatlands is common, e.g. about 25% of Finnish forestry and 22% of the Swedish forestry is done on peat soils (Minkkinen, Byrne et al. 2008).
- *Extraction of peat soils.* Peat soils are extracted for two main purposes. One is for peat fuels, and secondly peat soils are extracted for use in horticulture. There are also some other uses in some environmental technology solutions like sorbents in waste water treatment (Paappanen 2010). The most commonly used extraction method today is the milling method. New methods such as the biomass drier method are also tested for peat extraction.
- *After-treatment of peatlands.* Any peatland that has been subject to peat extraction or peatland forestry can be restored. In most cases this means that the land is rewetted, and/or re-afforested. The after-treatment until a stable system have been created will take relatively long time, typically at least 50 years (Holmgren, Alm et al. 2011).

The different land uses are commonly found in the literature and forms a basis for the wealth of studies found on the carbon cycles in peatlands. The land use types links to the terminology in the Intergovernmental Panel for Climate Change (IPCC) framework (IPCC 2006)[1].

The presentation of the different land uses are made based on scientific studies in the field. The fluxes will change over the year as a consequence of changing temperatures, hydrology etc. In order to provide comparable data annual fluxes have been compiled. In the approach to create a datasets of annual emission fluxes linked to various land use emissions we have relied on a number of already existing compilations of which the datasets found in the appendices in the PeatImpact report (Holmgren, Alm et al. 2011) is the most important. We have checked this to ensure that it includes the data from other sources (for example Kasimir-Klemedtsson, Klemedtsson et al. 1997; von Arnold, Hånell et al. 2005; Saarnio, Morero et al. 2007; Strack 2008; Joosten 2009; Maljanen 2010; Couwenberg 2011; Holmgren, Alm et al. 2011) but also to ensure redundancy is avoided. The compilation has not been possible to make calculations of the total CO_2 eq associated to each land use category. The main reason being that the data provided would not always include measurements of all the three GHG considered. Hence calculating CO_2 eq would often miss out one or two of the GHGs considered here.

The variations in emissions from different land use categories are displayed in boxplot diagrams. A boxplot diagram will provide information on a set of the descriptive statistics linked to a dataset. As a consequence of the large variations and skewedness seen in the compiled data median value will be provided as a measure of the middle value. A boxplot will provide information on the max and min values, lower and higher quartiles and also the median value. In addition to this there are outliers that illustrate cases where the data is outside the high and low values. The outliers are representing the max and min values in the dataset and displayed so in the tables (*Figure 4*).

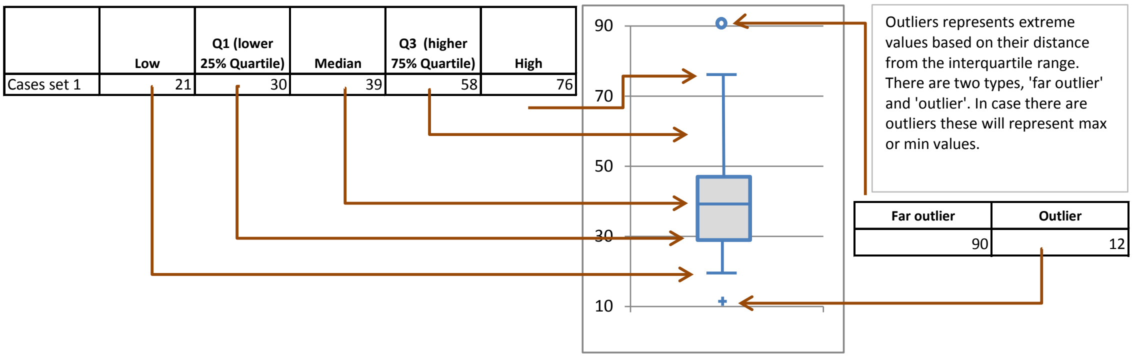

Figure 4: Boxplot and the information displayed.

The focus in this report is the emission fluxes from different land use and a review of existing LCA-studies on energy peat. The system boundary is set to the peatland and the production stages associated with extraction of peat and peatland after-treatment.

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[1] A similar terminology on land use is also found in the Fuel Quality Directive European Parliament (2009). "Directive 2009/30/EC of the European Parliament and of the Council of 23 April 2009 amending Directive 98/70/EC as regards the specification of petrol, diesel and gas-oil and introducing a mechanism to monitor and reduce greenhouse gas emissions and amending Council Directive 1999/32/EC as regards the specification of fuel used by inland waterway vessels and repealing Directive 93/12/EEC." Official Journal of the European Union **52**(L140/88): 62. and Renewable Energy Directive European Parliament (2009) "Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC." Official Journal of the European Union **52**, 62 DOI: doi:10.3000/17252555.L_2009.140.eng..

2.1 Approaches for monitoring of GHG emission from peatland.

There are basically two main methods for monitoring and measuring fluxes from peatland; i) the Eddy covariance method of measuring net ecosystem exchange (NEE) and ii) the chamber method (*Figure 5*).
The Eddy covariance method involves measuring the net exchange of CO_2 from an ecosystem. From a tower above the forest or land measurements are done of the CO_2 exchange, this will then include the uptake of carbon in the ecosystem (standing biomass, soil etcetera). Other restrictions are that there needs to be a relatively large homogenous area to be studied and the technology required is expensive.
The other option is the chamber method where the gas exchange is studied based on the system boundaries defined by the chamber. Gas chamber methods can be utilised for measuring CO_2, N_2O and CH_4. The chamber method involves less complicated technology than the Eddy covariance technology, but does not include the biomass accumulation in for example trees. Closed chamber methods and Eddy covariance methods both give similar results of monthly and annual NEE (Laine 2006).

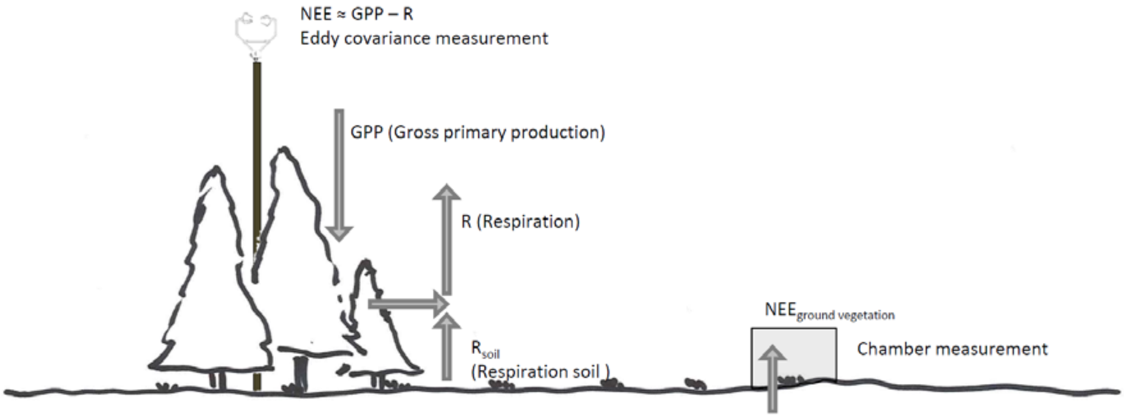

Figure 5: Simplified picture of the Eddy covariance and chamber methods

These methods do not fully cover the net ecosystem productivity as some small amounts of carbon are lost in for example run-offs. These losses are small in relation to the carbon cycles in for example the respiration (Holmgren, Alm et al. 2011).

3 Background to peat soils in Northern Europe

Boreal and subarctic peatlands store large amounts of carbon and contains about 20% of the global terrestrial carbon stock. In the boreal zone they account for about 34 % of the total boreal land area with the highest concentrations in Canada, Alaska, Northern Europe and Western Siberia (Holmgren, Alm et al. 2011). Due to drainage for forestry, cropland, peat production and infrastructure there has been a large decrease in pristine peatlands worldwide. Peatlands have been affected by anthropogenic activities for a long time and in Europe about 51 % of the original peatland area has been affected by drainage or other anthropogenic activities (Holmgren, Alm et al. 2011). In Finland and Sweden about 55 % and 15 % of the total peatland areas have been drained respectively. Approximately 10 % of the drained areas in these countries have been used for agriculture and about 90 % for forestry. Drainage is not a common practice for expanding land use in Europe today, in order to keep the land drained the drainage systems has to be maintained (Maljanen 2010). In Estonia the total peatland area is about 22 % of the mainland including both drained and natural peatland. Out of the total peatland area 70 % have been affected by drainage in Estonia for agriculture or forestry purposes (Salm, Kimmel et al. 2009; Salm, Maddison et al. 2012).

In Ireland peat soils cover approximately 20 % of the land area but only a fraction of this share is natural. Human activities such as peat mining and agriculture have affected 80 % of the peat soils. After peat extraction the abandoned extraction sites have been used for agriculture and commercial forestry in Ireland, similarly to other peat extraction sites in Europe (Wilson, Renou-Wilson et al. 2012). Sweden, Finland, Estonia and Ireland are important in the context peat and greenhouse gases since they represent four countries with high peatland area compared to other countries in Europe.

The interest of restoring peatlands is increasing partly because the soils of drained peatlands usually are sources of carbon dioxide and that after-treatment can decrease these emissions. It is also relevant to apply a suitable after-treatment alternative (afforestation or rewetting) on peatland areas when peat extraction has ceased in order to decrease the emissions. By after-treatment the emissions from the peat can be decreased, how much depends on the local character of the peatland, its previous use and the after-treatment alternative. The most commonly used active options include rewetting where the water table level is increased making the site become more like a pristine mire, and afforestation when trees are planted at the site. Rewetting can be done by discontinuing the maintenance of drainage ditches or actively raising the water table level. Neither of these methods is in large scale use in Europe today but efforts to reduce the climate impact of former extraction sites are making after-treatment projects more and more attractive. Other purposes of restoring drained and previously extracted peatlands are for recreational values and for wildlife preservation by turning former extraction sites into wetlands.

4 Emissions of greenhouse gases in the peat utilisation chain

4.1 Pristine mire and wetland

Release and accumulation of greenhouse gases is dependent on the type of peatland and the prevailing climate conditions, such as timing of snowmelt and geographical location. Wet conditions results in accumulation of carbon and CH_4 emissions and is the prevailing conditions in most natural pristine peatlands. Some studies suggest that the net ecosystem exchange of CO_2 in northern natural peatlands varies between sequestration of 220 g CO_{2eq} m^{-2} a^{-1} and release of 310 g CO_{2eq} m^{-2} a^{-1} (Strack 2008).

Hagberg & Holmgren (2008) compiled results from CO_2, CH_4 and N_2O fluxes from pristine mires from already existing studies and showed on significant variations. Hagberg and Holmgren (2008) showed that new measurements from 2007 were in contrast to earlier flux measures made from pristine mires. Earlier studies had shown a small uptake of CO_2 for both ombrotrophic and minerotrophic mires (about 50-80 g CO_2 m^{-2} a^{-1}) and the new measurements showed average emissions of 150 g CO_2 m^{-2} a^{-1} from ombrotrophic mires and an uptake of -230 g CO_2 m^{-2} a^{-1} for minerotrophic mires.

(Saarnio, Morero et al. 2007) reviewed fluxes of CO_2 and CH_4 from two study sites in southern Finland and showed that CH_4 emissions are generally higher from minerotrophic than from ombrotrophic mires. Measurements were made during a two year period and showed that the CO_2 exchange from boreal ombrotrophic peatlands are 55±190 g CO_2 m^{-2} a^{-1} and from minerotrophic peatlands -55±230g CO_2 m^{-2} a^{-1}. CH_4 emissions results from the same study indicated CH_4 emissions of about 6.7±5.3 from ombrotrophic sites and 17.3±13.3 g CH_4 m^{-2} a^{-1} from minerotrophic sites.

Kirkinen et. al. calculated greenhouse gas impacts from different peat fuel utilisation chains, including emissions from pristine peatland, forestry-drained peatlands and cultivated peatland including different after-treatment alternatives (restoration, afforestation). Results from this study showed an average emission of 23 g CH_4 m^{-2} a^{-1} at pristine mires (Finnish conditions). The study also presented an extensive overview of emission sources and sinks of the studied utilisation chains (Kirkinen, Minkkinen et al. 2007).

An extensive study from 600 Swedish mires showed that CH_4 emissions from Swedish mires could vary between 2-40 g CH_4 m^{-2} a^{-1}. This figure varies depending on if trees are growing on the mire and the surrounding area or not. Long-time Swedish measurements of CH_4 emissions also correspond with studies by Nilsson et. al. (2000) of 21 g CH_4 m^{-2} a^{-1} (Uppenberg, Zetterberg et al. 2001).

Salm (2009) estimates the global warming potential and annual emissions from Estonian peatlands, also using available flux data from studies in Finland, Sweden and Canada. Estonian peatlands situated in similar climatic conditions, peatland types and flora were assumed to be similar to already available flux data in Finland, Sweden and Canada. Annual emissions from Estonian peatlands were estimated to be 82-311 g CO_{2eq} m^{-2} a^{-1}. Annual efflux was 123-100 CO_{2eq} m^{-2} a^{-1} from drained peatlands and -41-112 CO_{2eq} m^{-2} a^{-1} from undrained peatlands. The results are obtained based on only two one? actual measurements of fluxes in Estonia; one by Ilomets (2006) and one by Minkinen (2007) of which one was based on measurements from Finland. As a result of drainage of Estonian peatlands Estonia´s nutrient poor fens and nutrient rich bogs have turned from being sinks to sources of carbon in general (Salm, Kimmel et al. 2009).

Salm et. al. conducted another study in 2009 including nine study sites in natural and drained peatlands in Estonia which covered areas with different land use practices; natural, drained, abandoned peat mining and active peat mining areas. Fluxes of CO_2, CH_4 and N_2O were measured with closed-chamber based sampling. CO_2 emissions were 150.9, 192.1, 284.5 and 174.1 g CO_2 m^{-2} a^{-1} from natural, drained, abandoned and active peat extraction areas respectively.

Emissions of CH_4 were 8.52, 2.37, 0.007 and 0.012 g CH4 m-2 a-1 for respective peatland. N_2O emissions were very small or negative except from peat extraction areas (0.019 g N_2O m^{-2} a^{-1}). The measurements showed significantly higher emissions of CO_2 and N_2O from abandoned and active peat extraction areas, and significantly higher CH_4 emissions from natural and drained sites. Overall the emissions from the studied sites corresponded with those of similar studies (Salm, Maddison et al. 2012).

According to the life cycle study of Hagberg and Holmgren, emissions from N_2O are negligible from pristine mires (based on Kasimir-Klemedsson 2001) and pristine peatlands might also act as small sinks of N_2O. Based on existing research N_2O emissions from undrained peatlands are low, generally <0.001 g N_2O m^{-2} a^{-1} (ombrotrophic) (Maljanen 2010). However, small net emissions of N_2O of about 0.02 g N_2O m^{-2} a^{-1} from pristine minerotrophic mires have also been shown based on (von Arnold, Hånell et al. 2005; Hagberg and Holmgren 2008).

4.2 Forestry on peatlands

As with emissions from pristine mires fluxes from drained forested peatlands also differ depending on the conditions. Depending on the characteristics of the tree stand and drainage level, forest drainage may result in a net uptake of carbon or a net release. Drained peatlands usually emit more CO_2 but less CH_4 than undrained peatland. The overall fluxes to and from drained forested peatland is further dependent on climatic region and site fertility.

CO_2 emissions from drained forestry peatlands vary greatly according to a number of studies conducted in Sweden and Finland. The main factors controlling soil CO_2 balance are fertility water table and temperature. The (Hagberg and Holmgren 2008) study made a distinction between high and low fertility drained forested peatlands, and used an average of 818 g CO_2 m^{-2} a^{-1} for high fertility peatlands and 458 g CO_2 m^{-2} a^{-1} for low fertility peatlands (only soil emissions included). However, according to literature on which these estimates are based, CO_2 emissions from drained forested peatlands lay between 257-1111 g CO_2 m^{-2} a^{-1} (based on measures in southern Sweden. Yet other studies suggest that CO_2 emissions vary between 719-1911 g CO_2 m^{-2} a^{-1}. The sink in CO_{2eq} at fertile sites is according to Ojanen (2013) -690±90 g m^{-2} a^{-1} and at poor sites -540±70 g m^{-2} a^{-1} (Ojanen, Minkkinen et al. 2013), if also the uptake in growing forests are considered.

Soil studies of emission fluxes at forestry-drained organic peatlands in Finland suggests that the soil is on average a CO_2 source of 190±70 g CO_2 m^{-2} a^{-1} at nutrient rich sites, but a CO_2 sink of -70±30 g CO_2 m^{-2} a^{-1} at nutrient poor sites (based on measurements from 68 sites in Finland). The more nutrient rich the site is the more likely it is that forestry will lead to a loss of carbon in the long term. (Ojanen, Minkkinen et al. 2013). N_2O emissions from drained forested peatlands have shown to be primarily dependent on soil fertility and tree species at the site. According to Hagberg and Holmgren, N_2O emissions from drained forested peatlands were estimated to 0.01 g N_2O m^{-2} a^{-1} (low fertility) and 0.5 g N_2O m^{-2} a^{-1} (high fertility). Generally, drainage can stimulate N_2O emissions on fertile or fertilized sites but generally can be stated that N_2O emission are lower in nutrient poor conditions whereas emissions can rise to 1 g N_2O m^{-2} a^{-1} on fertile drained pine fens which are nutrient rich. This relationship is also shown by Klemedtsson et. al. (2005) where different models was applied accounting for regional distribution and peatland types in Finland. Emissions of N_2O from drained forested peatlands according to this study fell between 0.17-0.31 g N_2O m^{-2} a^{-1}. Also here about half of this amount was released from nutrient rich sites (Alm, Narasinha et al. 2007).

Measures of fluxes during wintertime indicate that N_2O emissions can be significantly higher during wintertime; up to 3 g N_2O m^{-2} a^{-1} and N_2O emissions on an annual basis are therefore dependent whether wintertime fluxes are included in measures generally.

In the Finnish study (Ojanen 2013) N_2O and CH_4 combined stands for +40±10 g CO_{2eq} m^{-2} a^{-1} on fertile sites and +20±5 CO_{2eq} m^{-2} a^{-1} on poor sites.

Minkkinen et. al. (2007) showed that emissions of particularly CH_4 showed a negative exponential relationship between tree stand volume and CH_4 emissions. Sites with small timber volume released CH_4 after drainage (up to 4 g CH_4 m^{-2} a^{-1}) while larger timber volumes consumed the CH_4 (up to 1 g CH_4 m^{-2} a^{-1}). The turning point from source to sink was 140 m^3 biomass ha^{-1} a^{-1}. Indications for this relationship were also found for undrained mires, but the relationship was not as clear as for drained sites. Measures were made in various sites in Finland. According to the results, annual fluxes were small to negligible. Worth mentioning is that active productive forestry on drained peatlands will make the peatland to act as a CH_4 sink, regardless of the standing tree volume if sufficient drainage is

achieved (Minkkinen, Penttilä et al. 2007). According to Maljanen et. al. CH_4 emissions from ombrotrophic and minerotrophic sites drained for forestry are 1.24±1.64 g CH_4 m^{-2} a^{-1} and 0.59±1.36 g m^{-2} a^{-1} respectively (Maljanen 2010).
In drained forested peatlands maximum sequestration rates of -0.82 g CH_4 m^{-2} a^{-1} have been found. However, most drained peatlands remain as sources of CH_4. Generally emissions originating from ditches in the drainage network might be a major contributor to the total GHG fluxes; up to 4.5 % of the total emissions from forestry drained peatlands (Maljanen 2010). The maintenance of the drainage ditches is therefore relevant for the overall emissions from a particular peatland. If the vegetation in the ditches can be kept away the CH_4 emissions from the ditches are also likely to stay at a low level. Hagberg and Holmgren assumed that emissions of CH_4 is insignificant from low fertility drained forested peatland and 2 g CH_4 m^{-2} a^{-1} for high fertility sites. According to Alm (2007) which based measures on 30-year weather simulations, CH_4 uptake and emissions from drained forested peatlands are -0.82 to 3.5 g CH_4 m^{-2} a^{-1} (Alm, Narasinha et al. 2007).

4.3 Agriculture on peatlands

Agricultural use and cultivation on peatlands reduces emissions of CH_4 but on the other hand contribute to significant emissions of CO_2 and N_2O. This is due to crop management activities (i.e. soil tillage, irrigation) which leave the upper soil layers exposed to conditions where it rapidly decomposes, emitting CO_2. The highest overall emissions from peatlands are caused by using peatlands for agriculture: 48-4821 g CO_{2eq} m^{-2} a^{-1} according to Alm, 2007) (Alm, Narasinha et al. 2007). Other sources show even larger emissions. Emissions from cultivated peatland are dependent on crop species and the intensity of the land management. Fertilizers might also contribute to the emission.
(Maljanen, Hytönen et al. 2007) studied emissions from cultivated and abandoned peatland in Finland and showed that both CO_2 and N_2O emission from cultivated peatlands do not decrease with time while CH_4 might gradually increase after cultivation has ceased. Drained cultivated peatlands can either be sinks or sources for CH_4 depending on water table level and climatic conditions. The same study concluded that CO_2 emissions from cultivated peatlands can be high as long as 20-30 years after the cultivation at the site has ceased and that all cultivated peatlands were net sources of CO_2, irrespective of the crop species. Crop species and corresponding fluxes measured were grass (79-750 g CO_2 m^{-2} a^{-1}), barley (210-830 g CO_2 m^{-2} a^{-1}) and fallow land (690-1100 g CO_2 m^{-2} a^{-1}).
Estimates by Hagberg and Holmgren (2008) for Swedish cultivated peatlands indicated emissions of 1780 g CO_2 m^{-2} a^{-1} and 1.5 g N_2O m^{-2} a^{-1}. CH_4 emission are generally insignificant (Kasimir-Klemedtsson, Klemedtsson et al. 1997). According to Maljanen et. al. (2003) N_2O emissions were twice as high from cultivated organic soils compared to afforested peatland (Maljanen, Liikanen et al. 2003).
(Holmgren, Alm et al. 2011) concluded that CO_2 losses are generally higher from croplands (4650 g m^{-2} a^{-1}) than from grasslands (1900 CO_2 m^{-2} a^{-1}). Byrne et. al. (2004) studied emissions from peatlands in Europe and concluded that the CO_2 emission ranges from 1610 – 860 g CO_2 m^{-2} a^{-1} for ombrotrophic (nutrient poor) peatlands and 1500-1510 g CO_2 m^{-2} a^{-1} for minerotrophic (nutrient rich) crop- and grassland in Europe respectively (Holmgren, Alm et al. 2011).
In the boreal zone as well as in temperate zones CH_4 emissions are generally negative which is due to the fact that boreal peatlands generally are well-drained. Important for boreal peatlands is that cold winter seasons tend to increase N_2O fluxes.

(Holmgren, Alm et al. 2011) compiled emission data from cultivated peat soils in boreal, temperate and tropical zones based on a long list of authors. (Couwenberg 2009) summarized emissions found in recent literature on emissions from different climatic zones, land uses and peat production state. According to literature all three greenhouse gases show a large variation, but emissions from boreal grasslands on peat soils are lower than from croplands. Couwenberg et. al. further concludes that N_2O emissions from boreal soils are especially apparent in winter and thus become comparable to temperate areas.

4.4 Extraction of peatlands

During preparation for peat production above-ground vegetation is removed leaving the peat soil exposed until the after-treatment phase of the peatland. As a result of the drainage the moisture content is lowered. There are three types of energy peat available; milled peat, air-dried sod peat and artificially dried peat briquettes. The conventional method is milled peat where the milled peat is stored in stockpiles.

Emissions during the extraction phase mainly originate from the drained extraction area, surrounding area affected by the drainage and stockpiles (Strack 2008) and the following review is done from these three origins.

According to Hagberg and Holmgren the CO_2 emissions from the peat extraction area ranges between 230-1020 g CO_2 m^{-2} a^{-1}, which is also pointed out by Sundh et. al. (2000). Average emissions reported by Sundh et. al. are 600 g CO_2 m^{-2} a^{-1}. According to the latter study, total carbon dioxide emissions are estimated to 1000 g CO_2 m^{-2} a^{-1} during the full duration of the extraction period, which include stockpile emissions and other losses (Sundh, Nilsson et al. 2000). Summertime emission variations were higher (400-1020 g CO_2 m^{-2} a^{-1}) than wintertime emissions (280 g CO_2 m^{-2} a^{-1}). For the LCA calculations conducted in the study by Hagberg and Holmgren, 980 g CO_2 m^{-2} a^{-1} was used, and for calculations of radiative forcing by Zetterberg (2004), 1000 g CO_2 m^{-2} a^{-1} was used as an average. For drained peatlands with initially high emissions the emissions of CO_2 stayed high throughout the extraction period.

The literature is not clear on how to estimate emissions from the surrounding area. Some studies (i.e. Zetterberg et. a. 2004) assume that the surrounding area has less emissions that the extraction area due to less working of machines and increased growth of trees compared to the actual extraction area.

Milled peat extraction, which is the common extraction method in boreal regions, can cause high emissions initially (1948-2478 g CO_2 m^{-2} a^{-1}), especially if extraction takes place during wet and warm summers. According to Alm et. al. CO_2 emissions range between 695-4101 g CO_2 m^{-2} a^{-1}, 7.23 g CH_4 m^{-2} a^{-1} and 0.31 g N_2O m^{-2} a^{-1} based on a whole year basis. Emissions are generally higher during the summer season. CH_4 and N_2O emissions from peat extraction areas mainly originate from ditches and stockpiles. Stockpile CH_4 emissions are highest during wintertime and is dependent on the time by which the stockpiles resides on the extraction strips (Alm, Narasinha et al. 2007).

Estimates of CH_4 emissions from the extraction area show similar results from a number of studies presented in Hagberg and Holmgren and ranges between 0.3-7.2 g CH_4 m^{-2} a^{-1} being generally higher during summer conditions. An average emission of CH_4 is assumed to be 3.7 g CH_4 m^{-2} a^{-1} in the (Hagberg and Holmgren 2008) study based on Sundh et. al. (2000) and Alm et. al. (2007) and includes winter emissions. Other studies (Zetterberg 2004) propose similar results from the extraction area such as 2.1 g CH_4 m^{-2} a^{-1} as an average.

Drainage will increase growth of trees and other vegetation in the surrounding area and in the drainage ditches (due to poorer maintenance) which gives rise to a CH_4 emission in the surrounding area of 5.25 g CH_4 m^{-2} a^{-1} after drainage. Due to poorer maintenance of the ditches the CH_4 emissions from the surrounding area are assumed to be higher than from the extraction area. Assumptions based on Sundh et. al. (2000) and Nykänen et. al. (2000) states that 25 % of the original CH_4 emissions from the surrounding area is due to poorer maintenance of drainage ditches (Uppenberg, Zetterberg et al. 2001).

Zetterberg (2004) also studies the time aspect of peat extraction which shows that emissions of CO_2 are high during the first 5-10 years (1000 g CO_2 m^{-2} a^{-1}) to decrease linearly to 300 g CO_2 m^{-2} a^{-1} during the following years 11-25 (Uppenberg, Zetterberg et al. 2001). Emissions from stockpiles are also included in the study estimated to be 175 g CO_2 m^{-2} a^{-1}.

N_2O emissions from the extraction area are assumed to be 0.2-1 g N_2O m^{-2} a^{-1} and the same from the surrounding area (Uppenberg, Zetterberg et al. 2001). Holmgren et. al. (2004) reviewed studies by Nykänen et. al. (1996) who concluded that N_2O emissions from peat extraction areas were very small, but also that emissions were higher from newly opened extraction areas and in older extraction areas. Holmgren therefore assumed that emissions were initially high to slowly decrease and then increase again (to 0.15 g N_2O m^{-2} a^{-1}) by the end of the extraction period (Nilsson 2004).

4.4.1 Importance of residual peat and production technology

After peat extraction a certain amount of peat is left which will contribute to the emissions from the site after extraction. The residual peat layer is important for the overall net carbon balance of a cut-away peatland, but few studies are available covering the importance of the residual peat in detail.

(Hagberg and Holmgren 2008) make the assumption that emissions from afforested cut-away peatlands decrease exponentially from 1100 g CO_2 m^{-2} a^{-1} during the first rotation period. Since the residual peat slowly decomposes, emissions will also decrease slowly after afforestation. Nilsson (2004) assumes that the rate of decomposition during extraction is maintained until the residual peat is decomposed (Nilsson 2004). Even though afforestation leads to sequestration of carbon in growing biomass the residual peat layer will lead to relatively high CO_2 emissions, but not to the extent that it will have a significant impact on the results according to a study comparing Swedish and Finnish results. Holmgren (2006) concluded that an exponential decrease of the decomposition rate of residual peat seems more realistic than assuming static emissions. According to Holmgren (2006) based on Kirkinen et. al. (2007), the decomposing residual peat might contribute to small net emissions on forestry-drained peatlands with afforestation as after-use option (Nilsson 2004; Holmgren, Kirkinen et al. 2006; Kirkinen, Minkkinen et al. 2007). Moreover, the residual peat will contribute to the tree stand growth rate, so in practice as pointed out by (Väisänen, Silvan et al. 2013), the residual peat layer should not be completely removed.

The amount of residual peat left affects the net carbon balance on cut-away peatlands. Afforestation decreases CO_2 losses from cut-away peatland but might not always lead to a net carbon accumulation due to the high decomposition rate of residual peat. According to available literature the assumptions made by Hagberg and Holmgren (2008) and Kirkinen et. al. (2007) are the best available estimates of the importance of the residual peat. Kirkinen et. al. (2007) studied the cumulative radiative forcing of different peat production chains and assumed that the decomposition decreases exponentially from 1150 g CO_2 m^{-2} a^{-1} until 1.6 cm peat is left after 300 years. N_2O emissions associated with residual peat will also decrease in accordance with CO_2 emissions as the residual peat layer decomposes.

The amount of residual peat left at the site after extraction can be lowered using another production method called biomass-drier, by which the peat is extracted with an excavator and spread out with a spreader. Compared to the conventional milling method the biomass-drier method results in a more efficient drying and a faster extraction which leaves less residual peat. The method also reduces emissions and makes it possible to utilize smaller areas compared to the milling method and extraction can therefore be directed to areas with currently high greenhouse gas emissions (Silvan, Silvan et al. 2012).

Silvan et. al. (2012) compared the overall emissions from peat extraction areas using both the new excavation method and the conventional milling method. The study shows that CO_2 emissions were significantly lower at fields extracted with the new method (vegetation cover does not need to be removed prior to extraction and the area does not need to be well drained). Stockpile emissions, which are usually significant from milling-method areas, can be more or less disregarded with the new method as it does not leave any stockpiles at the extraction site. CH_4 emissions were slightly higher using the milling method. Nevertheless, an LCA conducted on both the new and the conventional method indicated that the peat extraction method used is of less significance than the type of peatland extracted. The biomass-drier technology however seemed to reduce the climatic impact slightly compared to the milling method. Consequently, choosing the most high-emission peatlands for extraction is according to this study more important from a greenhouse gas perspective than the actual production technology (Silvan, Silvan et al. 2012).
Another factor influencing emissions from peat extraction is the production time (e.g. the time it takes from the extraction operation starts to the time when extraction operation ceases). Väisänen et. al. (2013) studied peat production in high-emission level peatlands and points out that reducing the peat production time to one tenth and using better extraction methods could reduce emissions with as much as 90 %. The same study also concluded that the emissions from the residual peat layer are directly proportional to the amount of residual peat.

4.5 GHG emissions from after-treatment of peatlands

After-treatment of peatlands has gained increased attention in the last years as a way to decrease emissions. There are a number of different ways of achieving this. Here two after-treatment methods are discussed; i) rewetting and ii) afforestation.

4.5.1 Rewetting

When peatlands are rewetted the water level is raised and the conditions become similar to those before drainage and peat extraction started. Rewetting alters the decomposition of organic matter and slows down or stops the release of CO_2, but also creates anaerobic conditions which start releasing CH_4. Generally rewetted peatlands become carbon sinks to varying degrees. Studies of after-treatment activities for peatlands are few compared to studies of the previous production stages and little is known on the long-term carbon dynamics of peatland after-treatment.
After rewetting the peatland might again become a carbon sink sequestering CO_2. According to various studies reviewed in Hagberg and Holmgren, CO_2 uptake in rewetted peatlands range between 80-362 g CO_2 m^{-2} a^{-1}. Kirkinen et. al. (2007) presented a best estimate of 122 (28-270) g CO_2 m^{-2} a^{-1}. Rewetted extraction sites can be both sources or sinks of CO_2 depending on the time since restoration and vegetation cover (Maljanen 2010). Tuittila et. al. (2009) studied rewetted cut-away peatlands as a sink for CO_2 and concluded that the studied systems (cut-away peatlands in southern Finland abandoned in 1975) became carbon sinks two years after rewetting. The study also showed that if the water level is low at the rewetted site, the total CO_2 balance of the system reach a zero net compensation point only if weather conditions were favorable (Tuittila, Kommulainen et al. 1999). Wintertime emissions can sometimes exceed the uptake during the growing season (67 ± 202 g CO_2 m^{-2} a^{-1}) (Maljanen 2010). Other studies in Finland show other results from rewetting. Komulainen et. al. concluded that annual CO_2 emissions varied from 162-

283 g C m^{-2} a^{-1} in minerotrophic mires (e.g. nutrient rich) and 54-101 g C m^{-2} a^{-1} in ombrotrophic mires (e.g. nutrient poor) after rewetting (Komulainen, Tuittila et al. 1999). Yli-Petäys measured fluxes from regenerated peat trenches 50 years after abandonment and the results show on a CO_2 uptake of 80±190 g CO_2 m^{-2} a^{-1} including winter emissions. Restored forestry drained peatlands emitted CH_4 in the range of 3.35±1.77 g CH_4 m^{-2} a^{-1} and CH_4 emissions are highly dependent on the age of restoration. Studies on N_2O emissions are few, but studies available show on emissions of 0.55 g N_2O m^{-2} a^{-1} (without fertilization) and up to 2.0 g N_2O m^{-2} a^{-1} with nitrate fertilization (Maljanen 2010). Emissions of CH_4 gradually increase after rewetting (after being very small or insignificant before rewetting) but they do not reach the same level compared to pristine mires. About the same results are applicable to restored peatlands drained for forestry in which CH_4 emissions increase after rewetting but remains at a lower level than from pristine peatlands (Tuittila 2000). Other studies (i.e. Nilsson and Nilsson 2004, Kirkinen et. al. 2007) assume that CH_4 emissions are the same after restoration as for pristine mires. Hagberg and Holmgren (2008) assumed that CH_4 emissions were the same as for pristine peatlands (minerotrophic mires); 17 g CH_4 m^{-2} a^{-1} based on Alm (2007), and that this is a value associated with significant uncertainty (Hagberg and Holmgren 2008). After rewetting the cut-away peatlands become functionally more close to pristine peatlands which is shown in a study including colonization of cottongrass on rewetted cut-away peatlands. The vegetation (cottongrass) increases primary production decomposing under anoxic conditions releasing CH_4 (Tuittila 2000). Studies conducted in eastern Canada on rewetting of cut-away peatlands show that CH_4 emissions might be significantly higher from such sites than emissions from pristine mires (Basiliko, Blodau et al. 2007).

4.5.2 Afforestation

When peatlands are afforested after extraction activities have ended the growing tree stand will start sequestering carbon from the atmosphere. At the same time emissions occur from decomposing residual peat. Consequently, estimations of emissions to and from afforested cut-away peatlands are dependent on the forest productivity at the site (more trees sequester more carbon and vice versa) and the time considered (one or several rotation periods). The focus in the following review is on emissions occurring during the first tree stand generation (which is approximately up to 85 years in boreal deciduous forests). According to Alm et. al. (2007), afforestation of peatlands abandoned from cultivation or peat extraction can lower the climate impact during the first tree generation. However, due to the high decomposition rate of residual peat the net fluxes to and from the site, including the trees, might be a net carbon loss. Fluxes are further dependent on whether the tree stand is spontaneously regenerated or if the site is prepared by mechanical management prior to planting. In the latter case emissions might be higher due to a higher decomposition rate. According to Alm et. al. (2007) emissions of afforested cut-aways were on average 1397 g CO_2 m^{-2} a^{-1} (1008-1756 g m^{-2} a^{-1}), -0.05 g CH_4 m^{-2} a^{-1} (-0.03-0.09 g CH_4 m^{-2} a^{-1}), and 0.15 g N_2O m^{-2} a^{-1} (0.02-0.75 g N_2O m^{-2} a^{-1}) based on Mäkiranta et. al. (2007). Emissions from afforested organic croplands are very similar except from N_2O emissions which are higher, according to the same study (Alm, Narasinha et al. 2007). Afforestation of organic croplands will significantly lower the soil CO_2 emissions compared to cultivation.

N_2O and CH_4 fluxes do not change as a result of afforestation, and the soil remains as a small sink of CH_4. When the increased carbon sequestration of the growing tree stand is taken into account, afforestation can decrease the overall greenhouse impact from organic croplands.

Pristine peatlands normally have low N_2O emissions while drainage enhances N_2O emissions. N_2O emissions from afforested cut-away peatlands are in line with N_2O emissions reported from drained forested peatlands, but Maljanen (2012) found that N_2O emissions from afforested agricultural organic soils were similar to those from organic agricultural soils in active use. Low soil pH, high nitrate availability and low water table depth are important factors associated with high N_2O emissions. These results suggest that afforestation is not necessarily a way to reduce N_2O emissions from drained boreal peatlands. Moreover, the time period since cultivation practices ended or the age of the tree stand (deciduous or coniferous) does not seem to affect N_2O emissions. The average annual N_2O emission reported was 0.86±0.73 g N_2O m^{-2} a^{-1} from coniferous sites and 1.00±1.12 g N_2O m^{-2} a^{-1} from deciduous sites. Even decades after afforestation of former agricultural organic soils N_2O emissions can still be as high as emissions from agricultural organic soils in active use. (Maljanen, Shurpali et al. 2012). N_2O emissions from drained forested peatlands however seemed to depend on the tree species as reported by Hagberg and Holmgren based on von Arnold (2004, 2005) which reported ten times higher emissions from sites with deciduous forests (0.2-1.1 g N_2O m^{-2} a^{-1}) than from coniferous forests (0.04-0.09 g N_2O m^{-2} a^{-1}). The Hagberg and Holmgren study assumed that N_2O emissions are 0.15 g N_2O m^{-2} a^{-1} after afforestation to decrease linearly to 0.06 g N_2O m^{-2} a^{-1} after 45 years and then stay at that level. Alm et. al. reported N_2O emissions in the range of 0.02-0.75 g N_2O m^{-2} a^{-1} 9-35 years after afforestation based on Mikenranta et. al. (2007).

4.5.3 Importance of carbon sequestration in biomass

How much carbon the growing forests can sequester depends on many factors and only few studies are available on the topic. After peat extraction has ended the tree productivity and hence its carbon sequestration capacity is determined by residual peat left on the site, drainage effectiveness, nutrient availability and forest management practices.

Hagberg and Holmgren (2008) assumed based on available studies an annual forest productivity of 7.1 m^3 ha^{-1} a^{-1} on cut-away peatlands after afforestation. This is about the same as the productivity of drained forested peatlands with high productivity in Sweden. Assuming a rotation period of 85 years and a constant growth rate, this corresponds to an uptake of 820 g CO_2 m^{-2} a^{-1}. The productivity is dependent on the climatic region and might therefore be higher in southern regions and lower in northern regions. Forest productivity on drained peatlands in Sweden was on average 7.1 and 3.6 m^3 ha^{-1} a^{-1} for high and low fertility drained peatlands respectively (which corresponds to an uptake of 820 g CO_2 m^{-2} a^{-1} and 416 g CO_2 m^{-2} a^{-1}), and forest productivity on average mineral soils in Sweden was 6.2 m^3 ha^{-1} a^{-1} (Hagberg and Holmgren 2008).

CH_4 and N_2O fluxes of boreal organic afforested agricultural soils have been studied extensively using chamber measurement techniques, but the total CO_2 exchange for the system including the tree stand is less studied. According to Maljanen et. al. (2010) only one estimate of total CO_2 exchange has been reported from Finland by Lohila et. al. (2007). According to the former study, the CO_2 sequestration into the ecosystem exceeded (i.e. was able to compensate) soil emissions from the afforested agricultural soil 30 years after afforestation (Lohila, Laurila et al. 2007). Another study by Lohila suggests that CO_2 emissions can be decreased from agricultural peat soils with afforestation (or perennial crops) but that these strategies do not turn the total system into a CO_2 sink since the CO_2 loss from old decomposing peat will continue (Lohila 2008).

More measurements are needed in order to determine the long-term effects of afforested organic croplands such as if several tree stand rotations are taken into account and the life cycle of the timber products.

4.6 Emissions from Irish peatlands

Ireland has 16.5% of its area covered by peatland. This is a relatively high ration compared to other European countries (*Figure 17*). Ireland is in the Atlantic biogeographic area and the data from Ireland is presented apart from the data from boreal regions.
According to measurements conducted in a rewetted industrial cut-away peatland in Bellacorick in Ireland, the rewetted site became a net carbon sink after rewetting. N_2O emissions were, similarly to studies conducted in Finland and Sweden, small or negligible. The results from the Irish study show that rewetting as an after-treatment option was successful in restoring the carbon sink function of the peatland. The study also concludes, in accordance with other studies on rewetting of former extraction sites, that variation in greenhouse gas fluxes are large and that the study period should be longer to allow for more precise results taking into consideration the effects of growing vegetation etc. The study showed that rewetting of cut-away peatlands, similar to other studies of rewetting in the boreal zone, resulted in a sharp decrease in CO_2 emissions and small CH_4 emissions from the bare-peat areas. Estimates of the global warming potential (GWP) indicate that rewetting is likely to have reduced GWP by 87 % at the site (which means that the rewetted peatland has a significantly lower warming impact on the climate) (Wilson, Renou-Wilson et al. 2012).
Wilson et. al. (2018) measured fluxes from rewetted peatlands in Ireland in order to study whether rewetted peatlands will emit CH_4 as with pristine peatlands. According to the study carried out in Turraun in Ireland, the creation of wetlands probably increases the emissions of CH_4 (4.3-38.8 g CH_4 m^{-2} a^{-1} in year 1 and 3.2-28.8 g CH_4 m^{-2} a^{-1} in year 2). The rewetting however, taking into account also CO_2 and N_2O, lead to a reduced GWP of the peatland (Wilson, Alm et al. 2009).
In the CARBAL-project (carbon gas balances in industrial cut-away peatlands in Ireland) three types of after-treatments alternatives of cut-away peatlands were studied in Ireland; i) plantation of Sitka spruce, ii) natural regeneration and iii) wetland creation.
The first site was afforested with Sitka spruce in 1982 (19 years before the start of the study). Results from the site indicate that the net carbon sink was 1.22-1.28 tonne C ha^{-1} a^{-1} measured over a two-year period (the tree stand sequestered 7.92 tonne C ha^{-1} a^{-1} and emissions from the soil were 6.64-6.70 t C ha^{-1} a^{-1}).
The second site was abandoned after peat extraction in the 1970s and then naturally regenerated (mainly by birch and willow). Not surprisingly, the area with natural regeneration sequestered less carbon annually (2.23 t C ha^{-1} a^{-1}) and lost about 7.17-7.79 t ha^{-1} a^{-1} through soil respiration. In other words, the site was a net carbon source of 4.94-5.56 t C ha^{-1} a^{-1}.
Characteristic for the third site which was rewetted in 1991 are large variations in emissions ranging between 1.64-7.68 t C ha^{-1} a^{-1}. These variations can be explained primarily by variations in rainfall and water table level. Consequently, these results again underline the seasonal variations in rewetted peatlands.
Another conclusion from the study is that for rewetting to function optimal it is essential that the water table is maintained close to the surface, as aerobic decomposition occurs up to 10 000 times faster than anaerobic decomposition (Wilson and Farrell 2007). Water level is generally the strongest controller of variations in emissions (Laine, Wilson et al. 2007). Rewetting might also create higher CH_4 emissions and rewetting-strategies should therefore be to reach a state in which CH_4 losses are offset by CO_2 uptake, according to the authors. Of the three after-treatment alternatives examined, forestry seems to be the best option from a greenhouse gas perspective (Wilson and Farrell 2007).

A special characteristic of Irish peatlands are so called blanket bogs which occur in temperate maritime regions in flat or moderately sloping terrain where precipitation exceeds evapotranspiration. Blanket bogs also have a high water table and a high sea origin ion concentration due to its closeness to the sea. Even if blanket bogs are globally a rare type of peatland they are important in an Irish context since they cover approximately 13 % of the Irish land area (compared to only 3 % globally). A few studies exist regarding blanket bogs. According to Sottocornola and Kiely (2009) blanket bogs seem to be particularly sensitive to climate change since they are sensitive to hydro-meteorological variations (Sottocornola and Kiely 2009).

4.7 Variations in emissions from different land use management

In the previous sections (4.1 to 4.6) we have presented data on various measured and assessed emission fluxes linked to each land use category. As shown the variations are relatively large between the different sites where flux readings have been made. Below is a set of box-plot diagrams shown displaying the results from a compilation of available sources linked to measurement technique or GHG, and the land use type.
The Ecosystem net emission includes the uptake of carbon in the biomass and will thus give a picture of the carbon balance on the peatland. In *Figure 6* a boxplot of the NEE CO_2 balance is found.

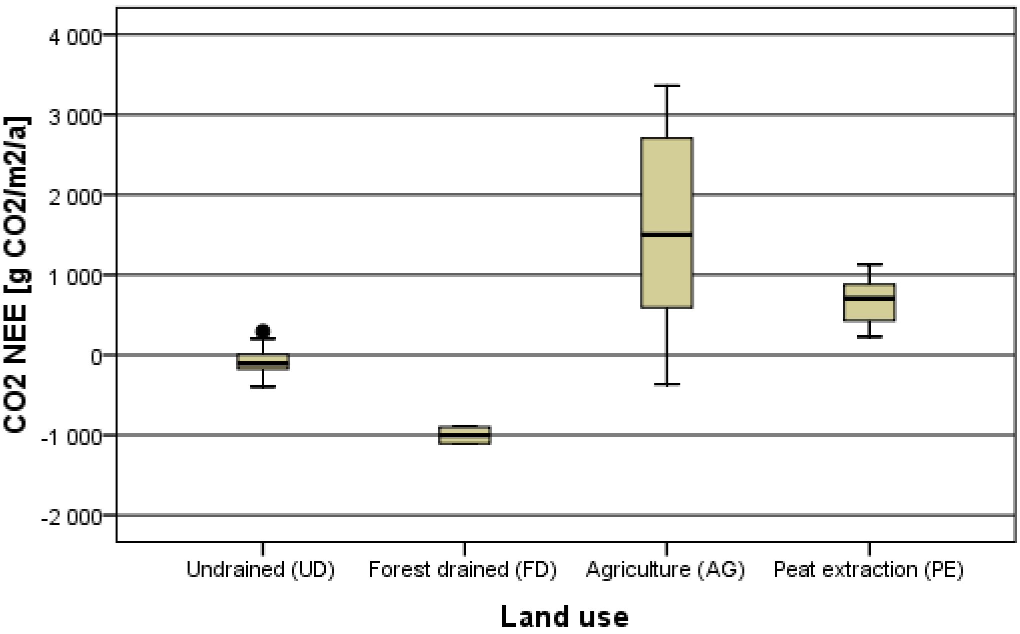

Figure 6: Net ecosystem emission, different land use regimes

The NEE is a snap shot of the carbon balance under different management regimes. In the case of drained forests it is a picture of the situation when there is a growing forest. In most cases this is a silviculture that eventually will be extracted. At that time the carbon will be released from the forest system. In the case it is used for construction material or other long lasting materials, the carbon will be “captured” in its solid biomass state. In the case the material is used for solid biomass fuels, or other products that eventually will be used for energy purposes in incineration or similar, then it is released to the atmosphere again. Silviculture in for example Sweden have for several years represented a net carbon uptake on a national level (see for example Naturvårdsverket 2012). This means that even though drained forest show uptake of carbon in the NEE measurements, the question on what the forest biomass will be used for ones it is extracted will arise.

As discussed in previous sections there are only small amounts of CH_4 emissions from drained peatlands as a consequence of the aeration of the soil. Along the drainage channels there will, however, be hot-spots where methane is released. Undrained peatlands and peatland under restoration will display the highest release of CH_4 to the atmosphere (*Figure 7*).

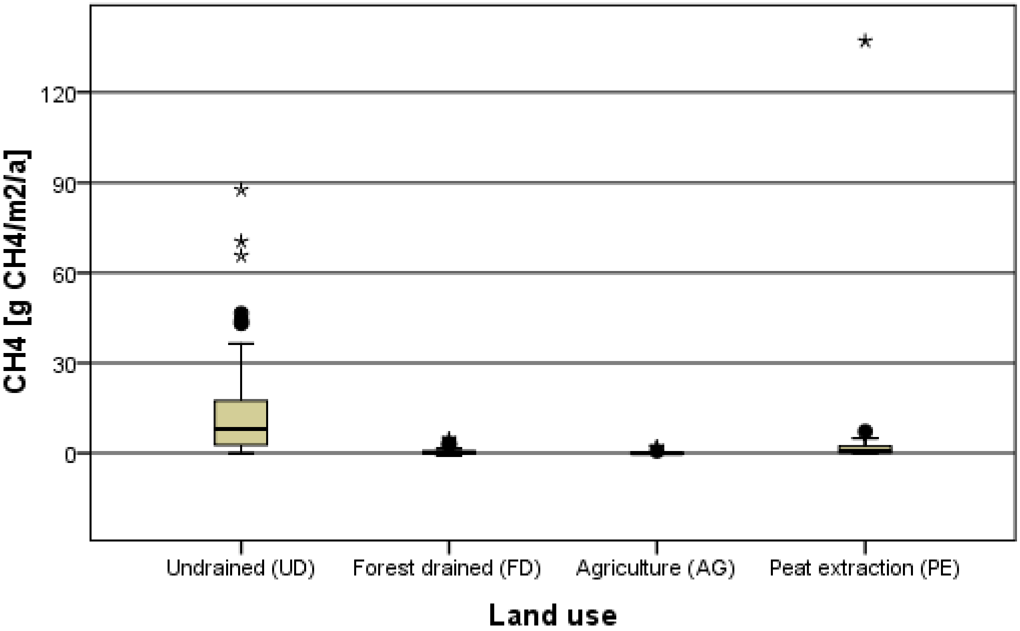

Figure 7: CH4 emissions from different land use management

Methane is a potent GHG with a GWP 25 times stronger than CO_2. Still the emissions of CH_4 will be substantially lower per m^2 of land as compared to CO_2 emissions even considering the GWP of methane. There can be small amounts of CH_4 oxidised in the soil, hence in some cases there is a small sink of methane in the soil.

The last GHG considered is N_2O. N_2O is almost 300 times as potent as CO_2 as a GHG which makes also release of small amounts of this gas important to consider. In *Figure 8* the data for emissions of N_2O as annual g of N_2O per m^{-2} are displayed in a box plot.

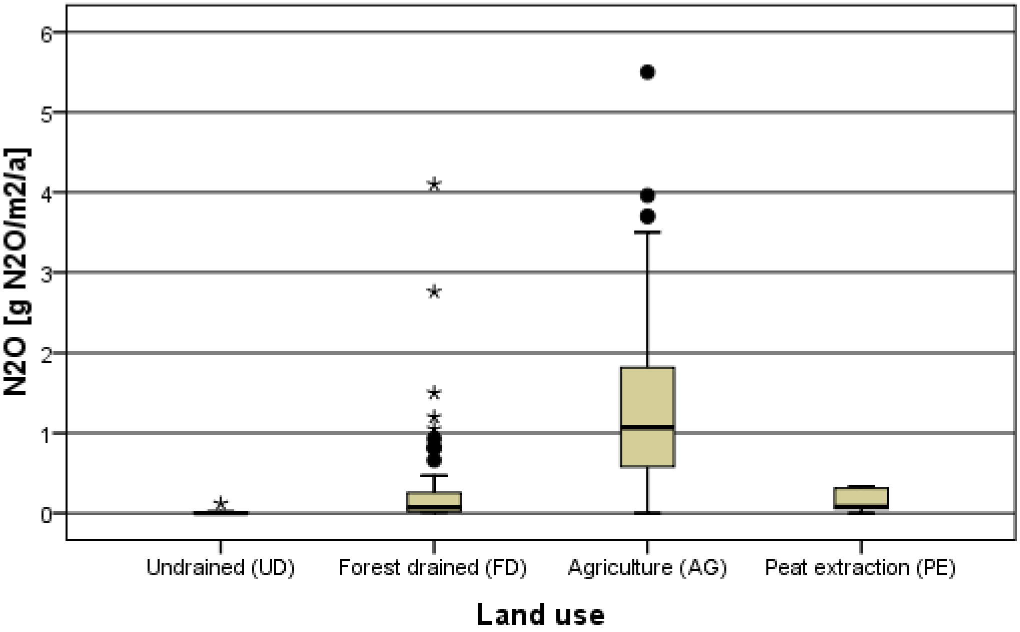

Figure 8: N2O emissions from different land use management

The results presented in *Figure 6 - Figure 8* show on the high variations found in the different fluxes recorded from peatland under different management regimes. Agricultural activates on peatland do however stand out as the management regime that results in highest emissions of both CO_2 and also N_2O.

4.8 Significance of the variations in peatland GHG emissions

Different peatlands have different emission profiles and the climate impact of energy peat production will depend on the peatland in question and the prevailing conditions. Most measurements must therefore be interpreted as a static picture of the emissions at that particular time at that particular site. It is clear that emissions can differ significantly from one site to another. The most important parameters determining the variations in peatland emissions are:

- Water table level
- Nutrient level
- Temperature
- Overall climatic conditions (such as precipitation as well as seasonal variations)

Variations are also significantly affected by management practices and the after-treatment alternative chosen.

By modeling, emissions can be estimated in a longer time frame and then delimitations and assumptions must be made which also affect the results. Most researchers agree that all agricultural organic soils are large sources of CO_2 and that these emissions can be persistent over time, at least in a medium time perspective of 20-30 years. Agriculture seems to be the worst alternative for managed peatlands mainly because of the tillage and soil management that come with the crop cultivation which increases emissions.

The choice of peatland and after-treatment alternative has great implications for the total emissions from peat production and largely determines the overall emission profile (i.e. CH_4 emissions in pristine peatlands or CO_2 emissions from drained sites).
The literature is not clear about how to consider the emissions from the surrounding area, which was or is usually affected by drainage. Some studies neglect these areas since vegetation growth is higher than the extraction site and that the situation is more alike a pristine state. Discontinuing ditch maintenance can increase the CH_4 emissions. (Väisänen, Silvan et al. 2013) suggest that peat extraction should be directed to peatlands which i) currently emit high amounts of greenhouse gases and ii) have the potential to increase forest growth and thereby carbon accumulation in forest. The study also proves that the climate impact of peat production can be reduced by choosing the most emitting peatlands for extraction. Similar conclusions are made in for example (Hagberg and Holmgren 2008).

4.9 The importance of emissions from residual peat and production method

The literature is not clear on the importance of the residual peat layer for the overall emissions. Other aspects seem to be more important such as the peat production time, the after-treatment method and the extraction method. Nevertheless, the importance of the residual peat should not be neglected. Based on available knowledge the residual layer seems to have a significant impact, and that the emissions are highest when extraction ceases to slowly decrease. If afforestation is chosen as after-treatment option the residual layer has a positive effect on the tree stand so removing it completely will probably decrease the carbon binding capacity.
The extraction method used (milling or biomass drier) has minor impact on the results. By using the biomass drier method, the surface layer of the peat does not need to be removed and the emission from a large open milled extracted field is avoided. However, the emissions from the site extracted with the new method are higher per area than from the milled fields. Out of the few studies conducted comparing these two methods; it appears that the two methods principally have the same total impact. This depends on the fact that the emissions from the site extracted with the new methods are higher than from the milling method, and the two will in practice level out. Far more important for the total results are, again, the emissions from the peatland and whether the peatland is a large or small source of greenhouse gases.

5 Climate impact from energy peat utilisation – LCA review

In this part of the report a comparative review is made of five life-cycle analyses of energy peat utilization. The reviewed reports are Hagberg & Holmgren (2008), Kirkinen et. al. (2008), Kirkinen et. al. (2007), Nilsson & Nilsson (2004) and Väisänen et. al. (2013). All reviewed studies are estimating the climate impact of energy peat utilization, however from slightly different approaches and with different assumptions and delimitations. The review mainly focuses on the results from the studies in terms of climate impact, based on the system boundaries and the assumptions made. The scenarios presented are mainly accumulated radiative forcing, showing the climate impact over a long time span.

In life-cycle analyses of climate impact from different fuels, radiative forcing and global warming potential are commonly used to describe the climate impact from different fuel chains. For instantaneous emissions, global warming potential (GWP) is a common measure to illustrate the climate impact from emissions that occur during a short time interval. For longer time periods, however, which are important in life cycle analyses, it is more relevant to use radiative forcing which illustrates the climate impact as a function of time. In practice, radiative forcing measures the warming of the climate and is in this review based on the three greenhouse gases CO2, CH4 and N2O.

Figure 9 shows the results for the climate impact from three energy peat utilization scenarios over 100 years: pristine peatlands – rewetting, forestry-drained peatland – afforestation and cultivated peatland – afforestation. Included in the figure are also the climate impact for coal, oil and natural gas. Figure 9-11 is based on LCA-results from Hagberg & Holmgren 2008, Kirkinen et. a. 2007, Seppälä et. al. 2007 and Zetterberg & Chen 2013.

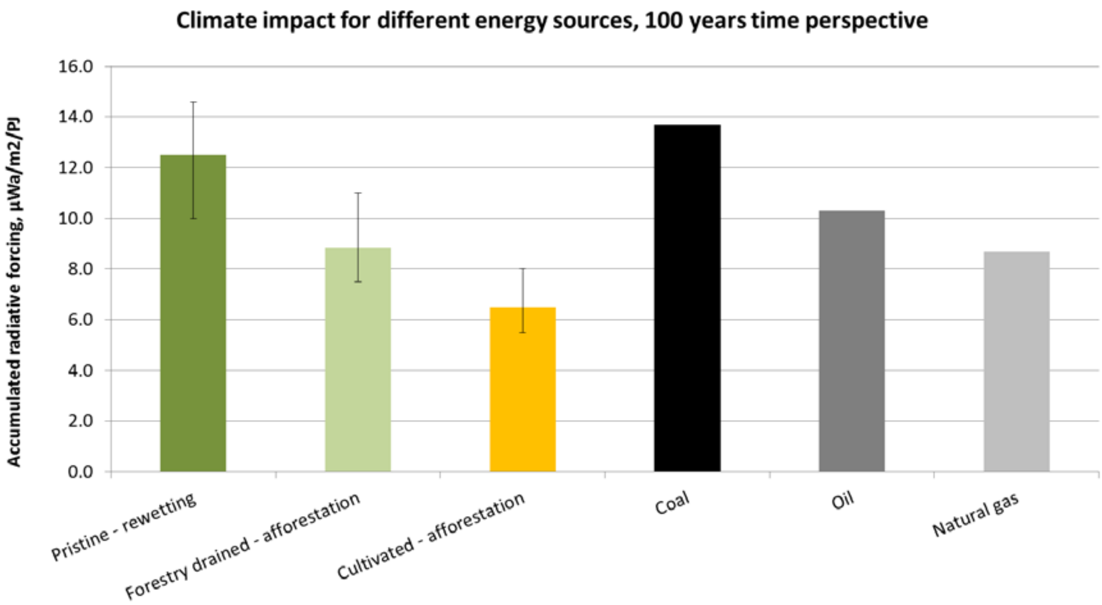

Figure 9. Summarized climate impact (accumulated radiative forcing) after 100 years for different energy peat utilization chains and fossil fuels. Three peatland scenarios are presented and compared with the climate impact from coal, oil and natural gas. The results show that the climate impact from peat utilization can be lower than coal in 100 years. Based on Hagberg & Holmgren (2008), Kirkinen et. al. (2007), Seppälä et. al. (2007) and (Zetterberg and Chen 2013).

In Figure 10 the impact of the nutrient content of the peatland is shown for forestry-drained peatlands aftertreated with afforestation. As can be seen from *Figure 10* nutrient rich forestry-drained peatlands have a higher climate impact in 100 years compared to forestry-drained nutrient poor sites.

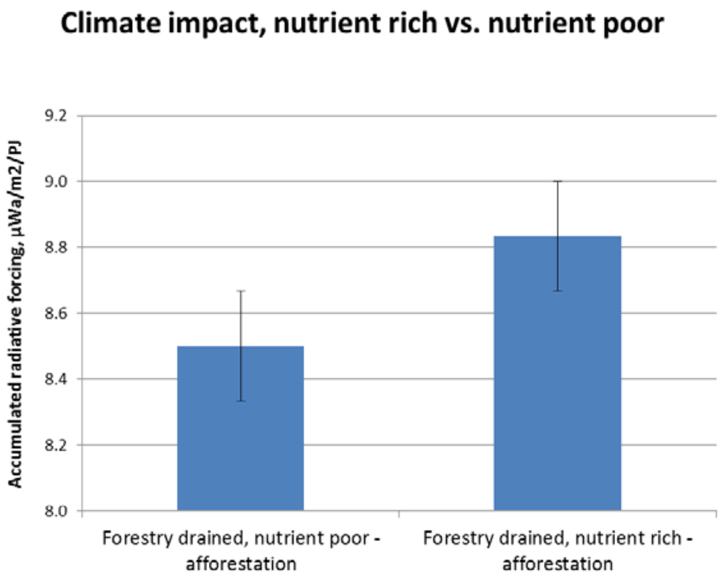

Figure 10. The difference in climate impact from forestry-drained peatlands depending on the nutrient content of the peatland over 100 years.

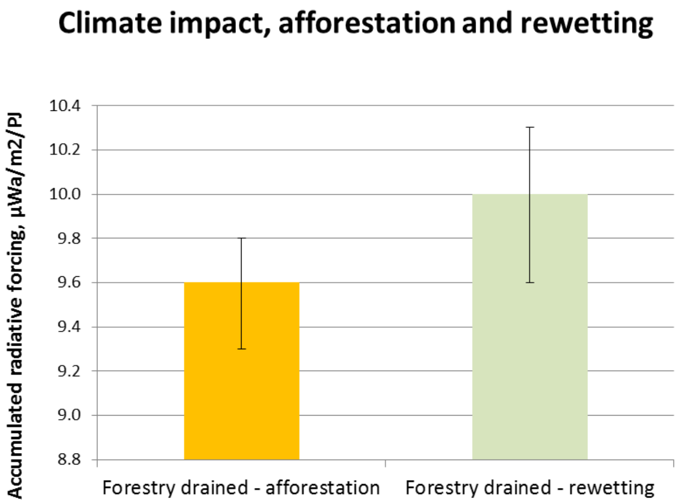

Figure 11. Difference in climate impact depending on after-treatment method applied. Over 100 years rewetting has a slightly higher climate impact than afforestation.

5.1 Potential reduction by using best-case production

Hagberg & Holmgren (2008) made a scenario showing on possible "best-case" situation of energy peat production. This scenario is based on the highest emissions from available literature (mainly von Arnold 2005, von Arnold 2004 and Maljanen et. al. 2007). The scenarios are presented in Figure 12 showing best cases for forestry drained sites and cultivated peatlands with afforestation as after-treatment option.

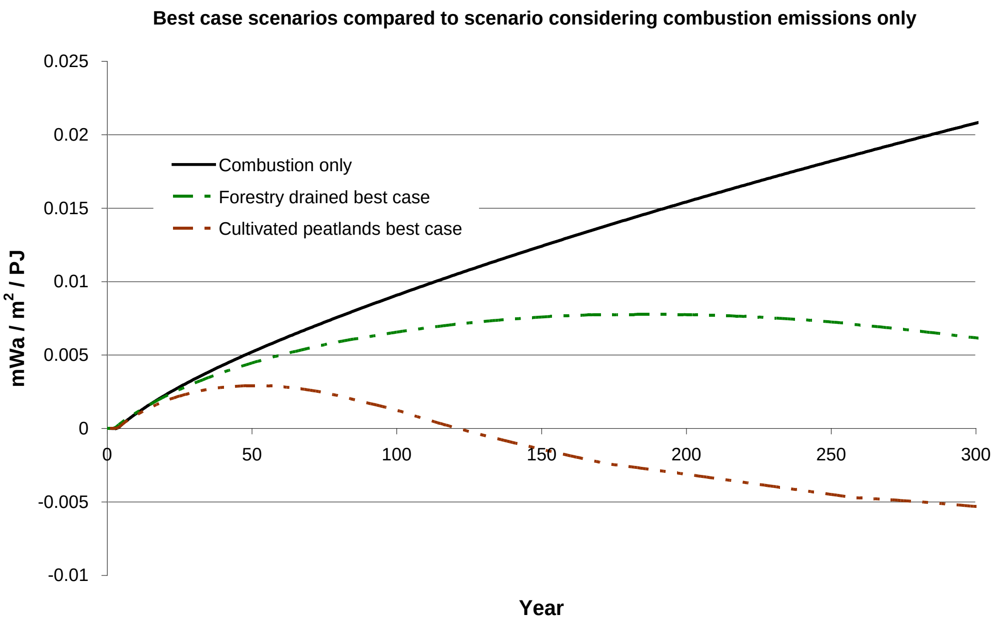

Figure 12. Combustion emissions only compared to two best case scenarios: forestry-drained and cultivated peatlands. The scenarios are based on the highest emission values in literature. In the combustion only scenario a default emission factor of 106 g CO_2/MJ was used. (Hagberg and Kristina Holmgren 2008)

The black line in Figure 12 represents the climate impact when only considering the peat combustion stage. After 100 years both scenarios are better (cultivated peatland scenario 87 % lower and forestry drained scenario 28 % lower). After about 140 years (when the cultivated peatland scenario cuts the x-axis in Figure 12) the cultivated peatland scenario shows a positive impact on the climate (i.e. a cooling effect). However, it is important to note that the data for Figure 12 is based on high peatland emission values (e.g. soil CO_2 emissions of 3550 g m^2 a^{-1} and 1111 g m^2 a^{-1} for cultivated peatlands and forestry drained peatlands respectively which is not the case if average values are used) in order to illustrate the importance of the peatland emissions.
A comparison with average peatland scenarios (based on average peatland emissions in literature), shows that the climate impact of the forestry drained scenario is 0-4 % lower than combustion only.

Using high-emission level peatlands for peat extraction in order to reduce the climate impact as much as possible is pointed out also in other LCA-studies of energy peat. To what extent emissions can be reduced is studied by Väisänen et. al. (2013). The incentive behind the study by Väisänen et. al. (2013) is that other LCA studies are using average emission values to determine the climate impact. Average values will generally produce a result on climate impact that is the same between studies and it is therefore relevant to estimate the potential reduction by using emission estimates high-emission level peatlands. The approach used by Väisänen et. al. (2013) differs from other studies because a system expansion approach is applied (including e.g. energy production in boilers and fuel substitution impacts on the system). In the study, peat was assumed to replace coal use at a local power-plant in Finland (replacing 20 % coal with peat gasification) and the peat was assumed to originate from nearby high-emission peatlands (Väisänen, Silvan et al. 2013). Results indicated that the emission levels from the unutilized peatland before extraction is determining the climate impact of energy peat when it replaces coal. Three time periods were studied: 15, 50 and 100 years and the results show that the emissions from peat fuel utilization are lower than coal emissions in the long term (50 or 100 years) but not in the short term (15 years). The study shows that basically three factors will have a significant impact on the results: i) the utilization of high-emission peatlands, ii) shortening the extraction time, and iii) removing the residual layer as much as possible (Väisänen, Silvan et al. 2013).

Nilsson & Nilsson (2004) (Swedish study) and Kirkinen et. al. (2007) (Finnish study) estimated the climate impact of energy peat compared to coal. Both studies show the climate impact of different peat fuel utilisation scenarios and uses accumulated radiative forcing calculations to show on the climate impact. The differences between the studies are significant, mainly due to methodological differences. The main difference is assumptions regarding peatland emissions which are higher in the Swedish study. Both studies show that using cultivated peatland results in lower climate impact than coal in a 100-year perspective and that the use of pristine mires causes higher greenhouse impact than using already drained peatlands. The differences between the studies mainly refer to different uptake and emission values for the after-treatment phase and the reference scenario (the non-utilisation chain).
Figure 13 and Figure 14 show the accumulated radiative forcing in the Swedish and Finnish study respectively when afforestation is used as after-treatment method:

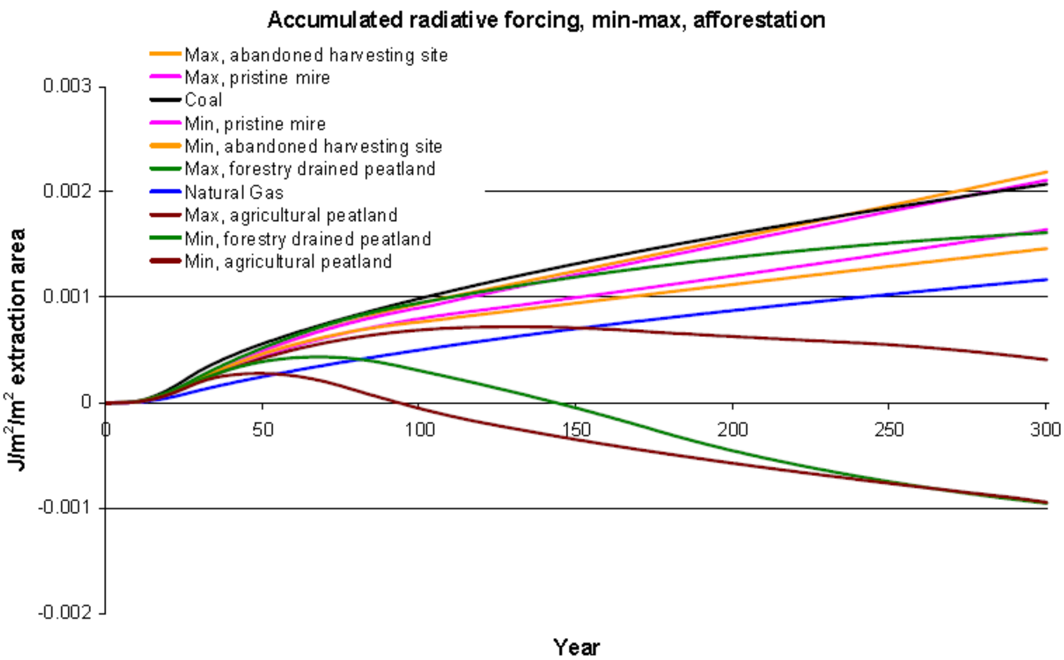

Figure 13. Accumulated radiative forcing of peat production scenarios according to Nilsson (2004). After-treatment option is afforestation. A minimum and maximum climate impact production chain is presented for each scenario.

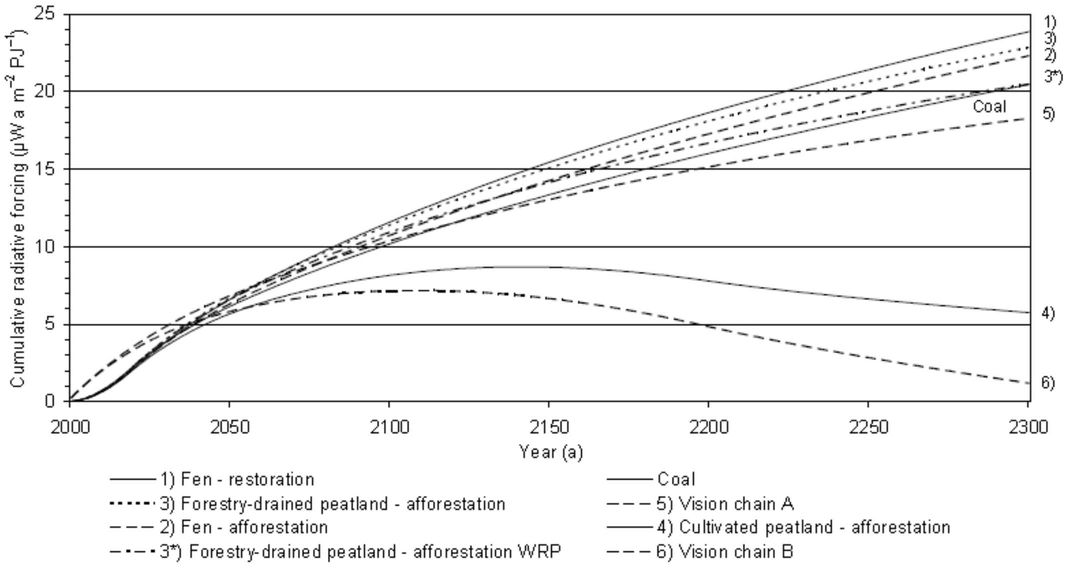

Figure 14. Accumulated radiative forcing as presented in Kirkinen et. al. 2007 (Kirkinen, Minkkinen et al. 2007).

The most significant difference between the Swedish and Finnish study are the forestry-drained peatland chains and is mainly due to the input data to the calculations. A review of the studies was made by Holmgren et. al. (2006) which shows that the Finnish CO_2 emissions from forestry drained peatlands are lower than the corresponding chains compared to the coal chain. Another important difference is that the surrounding area was considered in the Swedish study but not in the Finnish study. Considering the surrounding area will lead to higher emissions (see chapter 4.4).

5.2 System boundaries

5.2.1 Surrounding area

One of the most important factors determining the final results from LCA studies are the assumptions made regarding the surrounding area. The surrounding area is the area next to the peatland that might be affected by drainage. To what extent the surrounding area is affected is determined for example by the peat layer depth and drainage effectiveness. Different studies make different assumptions on this issue. The discussion on the delimitations of the surrounding area is foremost relevant for pristine mires, since forestry-drained and cultivated peatlands are already drained when extraction starts and that additional emissions from the surrounding area might be insignificant. The surrounding area is therefore not very important for forestry-drained and cultivated peatlands.

In the study by Nilsson & Nilsson (2004) the surrounding area was assumed to be as large as the extraction site and that the peat layer was half as thick in the surrounding area. In the study by Kirkinen et. al. (2007) the emissions from the surrounding area were not considered and it was assumed that the impact of the surrounding area was relatively small. No numerical estimates of the impact of the surrounding area on the radiative forcing are presented in the reviewed reports. What can be concluded is that the surrounding area will have an impact on the results depending on the character of the peatland. The size of the impact will be highest from pristine mires that are drained and lower from already drained areas. Grönroos et. al. (2012) emphasize that the inclusion of the surrounding area for cultivated peatlands are highly questionable since the area is used for agriculture (Grönroos, Säppälä et al. 2012). In the study by Hagberg & Holmgren (2008) the size of the surrounding area was assumed to be insignificant from forestry-drained sites and cultivated peatland and half the size of the extraction area for pristine peatlands. The available studies covering this issue (Nilsson and Nilsson 2004; Holmgren, Kirkinen et al. 2006; Seppälä, Tuovinen et al. 2010; Grönroos, Säppälä et al. 2012) seem to agree on the latter view of the surrounding area. Assumptions on the surrounding area in the different studies are presented in Table 1.

Table 1. Assumptions regarding the surrounding area in the reviewed studies.

Hagberg & Holmgren 2008	Kirkinen et. al. 2008	Kirkinen et. al. 2007	Nilsson & Nilsson 2004	Väisänen et. al. 2013
Minor impact for already drained peatlands. For pristine peat lands the area is assumed to be 50 % of the extraction area.	Information on surrounding area not found.	Not considered	Same as the extraction area and surrounding peat layer half as thick compared to extraction site. A static oxidation rate of -1 ton C ha^{-1} a^{-1} is assumed to occur 20 years after afforestation starts.	Not clear

Assumptions regarding the carbon sequestration in forest are presented in Table 2.

Table 2. Assumptions regarding carbon sequestration in growing forest in the reviewed studies.

Hagberg & Holmgren 2008	Kirkinen et. al. 2008	Kirkinen et. al. 2007	Nilsson & Nilsson 2004	Väisänen et. al. 2013
The CO_2-uptake used is -820 g m^{-2} a^{-1}. The three growth is 7.1 m^3 ha^{-1} a^{-1}. A rotation period of 85 years is assumed. 80 % of the carbon is removed from the area while 20 % is assumed to be left and decomposed at site during rest of the rotation period. Uptake is assumed for all rotations. An instant release of CO_2 from standing biomass is assumed every rotation period. Only the increased tree growth compared to the former use of the mire is considered.	Assumption that the carbon in standing trees is used for energy purposes after cutting.	The CO_2-uptake in average is assumed to be -448 g m^{-2} a^{-1} in the standing trees. -147 g m^{-2} a^{-1} is in average accumulated above ground (forest litter) and -15 g m^{-2} a^{-1} is accumulated underground. The accumulation is accounted for an average uptake during the half rotation period which gives 5.5 kg C m^2 in standing trees.	With a rotation period of 70 years (southern Sweden) a growth rate of 8.5 m^3 ha^{-1} a^{-1} is assumed. The CO_2 uptake is then -979 g m^{-2} a^{-1}. An accumulation forest litter of - 183 g m^{-2} a^{-1} is assumed in nutrient rich areas (70 years rotation) and -81 g m^{-2} a^{-1} in poor sites (90 years rotation). The accumulation occurs evenly distributed during the entire first rotation period.	Included. No numerical values in text for how much the uptake is in standing trees. The forest litter accumulation alters between -130 to -80 g m^{-2} a^{-1}.

5.2.2 Residual peat

Soil emissions from the decompositions of residual peat is an important factor for the climate impact (see also chapter 4.9) and different studies make different assumptions regarding this issue. At nutrient poor sites the residual peat might lead to net emissions even if the carbon binding capacity of the tree stand is considered, but these emissions are small compared to, for example, emissions from the extraction area. More research is needed in order to judge how much remaining peat can be left after extraction without disturbing biomass growth. The significance of the residual peat is lower if the area is rewetted since the conditions then will be waterlogged and oxidization of the peat is altered.

In Hagberg & Holmgren (2008) two peat milling techniques are compared where the conventional technique assumes to leave 20 cm layer and the new technique is assumed to leave 5 cm (Hagberg and Kristina Holmgren 2008). In Väisänen et. al. (2013) the residual peat layer is estimated to stand for approximately 25 % of the total lifecycle emissions from peat in 100 years perspective (Väisänen, Silvan et al. 2013). Assumptions made regarding the residual peat are presented in Table 3.

Table 3. Assumptions regarding the residual layer in the reviewed studies.

Hagberg & Holmgren 2008	Kirkinen et. al. 2008	Kirkinen et. al. 2007	Nilsson & Nilsson 2004	Väisänen et. al. 2013
5 cm with new peat milling method and 20 cm with conventional milling method	Not clear in report.	Included (one scenario without). 20 cm thick layer. The layer decompose from 15 000 g C m^{-2} to 1200 g C m^{-2} in 300 years	Included. A 20 cm thick layer is assumed. Oxidation rate of -1000 g CO_2 m^{-2} a^{-1} first 22 years after the extraction ends and then linearly decreases	Included. The residual peat layer emits 18 g COeq/MJ energy peat at gate, which is 25 % of the total life-cycle emission in 100 years

5.2.3 Time aspect

The choice of time period over which the calculations are made is important. According to the calculations in the reviewed studies, the importance of the combustion emissions is lower the longer the time perspective considered. However, as noted in Grönroos et. al. (2012), it might be misleading to use a time perspective longer than 100 years because climate mitigation action needs to be quicker than 300 years. This is especially relevant in scenarios where the climate advantage of using energy peat compared to the fossil reference comes first after two or three hundred years.

The time aspect is important not only for radiative forcing calculations but also for the fluxes to and from the system, which will be dynamic and change more during a longer time span. In the case of afforestation or rewetting as already gone through in section 4.5.1 and 4.5.2, tree sequestration rates and drainage conditions can change considerably during a

300 year perspective which will affect the results. In the case of afforestation it is also reasonable to assume that the tree biomass will be utilized or affected by forestry management activities during the time period and the use of the wood products are not considered in any of the reviewed reports, except from Väisänen et. al. where wood is used as energy.

Other complicating factors getting greater the longer the time span are the impact of climate change on forest productivity, changes in precipitation or albedo etc.

5.2.4 Peat – combustion emission factors

The default emission factor (combustion) for peat used in the EU-ETS is 106 g CO_2/MJ. However there are some variations in the emission factors for peat combustion that are used in the reviewed LCA-studies., especially when CH_4 and N_2O are included in the comparison.

In Hagberg & Holmgren (2008) the average emission factor for CO_2 used is 105.2 g/MJ. The same factor is used in Nilsson & Nilsson (2004). The factor is used for peat from the conventional peat milling method with a moisture content of 45 %. A moisture content of 30 % is considered for peat extracted with the new milling method. The emission factor is therefore lowered to 100 g/MJ. It can be discussed whether this lowering is appropriate or not. An oxidation factor of 99 % is introduced which means that combustion emission factor finally used is 104.1 g CO_2/MJ for peat with 45 % moisture content and 99 g CO_2/MJ for peat with 30 % moisture content. It is not clear from the reviewed studies if the oxidation factor is used due to incomplete combustion or the oxidation of the fuel before combustion.

The reference to the combustion emission factor in Kirkinen et. al. (2008) is (Kirkinen, Minkkinen et al. 2007). The factor for CO_2 is estimated to 105.9 g CO_2/MJ (lowest 101.1 and highest 106,5). The same factor is used in Kirkinen et. al. 2007 and in Väisänen et. al. (2013). The reference is Vestirinen, R (2003).

There are greater uncertainties in the emission factors from CH_4 and N_2O than for CO_2. Both of them are highly dependent on the combustion technology used. The emission factors for peat combustion used in Kirkinen et. al. (2008) are based on a specific combustion technology for a fluidized bed boiler (FB-boiler). Kirkinen et. al. (2007) uses Finnish average values from 1990-2003 from the national inventory reports to UNFCCC.

The emission factor for CH_4 used in Hagberg & Holmgren (2008) is 5 mg/MJ which is an estimated average value for Swedish heat and power plants (Uppenberg et. al. 2001). Same factor is used in Nilsson & Nilsson (2004) but with the reference to the earlier version of Uppenberg et. al. (2001). The emission factor for CH_4 in Kirkinen et. al. 2008 is estimated to 3 mg/MJ (low 1.5, high 4.5 mg/MJ), in Kirkinen et. al. (2007) 8.5 mg/MJ and in Väisänen et. al. (2013) 5 mg/MJ.

The emission factor used for N_2O in Hagberg & Holmgren (2008) and Nilsson & Nilsson (2004) is also a Swedish average value and is estimated to 6 mg N_2O/MJ peat with the reference Uppenberg et. al. (2001) In Kirkinen et. al. (2008) the factor is lower, 5 mg/MJ peat and is estimated value for a FB-boiler and the Finish average value used in Kirkinen et. al. (2007) is 12.8 mg/MJ. Väisänen et. al. (2013) has a much lower value of 2 mg/MJ.

Counted in carbon dioxide equivalents the two Swedish studies have the lowest values of 106 g CO_{2eq}/MJ followed by Väisänen et. al. (2013) with 106.6 gCO_{2eq}/MJ. The highest value is found in Kirkinen et. al. (2007) with 109.9 CO_{2eq}/MJ.

The combustion emission factors for peat used in the reviewed studies are presented in Table 4.

Table 4. Combustion emission factors for peat used in the reviewed studies.

	Hagberg & Holmgren 2008	Kirkinen et. al. 2008	Kirkinen et. al. 2007	Nilsson & Nilsson 2004	Väisänen et. al. 2013
Peat	**106.0** g CO_2eq/MJ conventional and **100.9** g CO_2eq/MJ for new milling method. Oxidation factor of 0.99 is used	**107.5** g CO_2eq/MJ, fluidized bed-boiler	**109.9** g CO_2eq/MJ, average Finnish value. (Same value for g CO_2/MJ as in Kirkinen et. al. 2008, both CH_4 och N_2O is higher	**106.0** g CO_2eq/MJ. Average Swedish value. Same as in Hagberg & Holmgren 2008	**106.6** g CO_2eq/MJ

5.2.5 Coal – Life-cycle emission factors

Hard coal, bituminous coal or lignite have different CO_2 combustion emission factor. In most reviewed studies the coal is not specified but it is probably hard or bituminous coal that is assumed due to the fact that lignite has too low energy density for profitable export to Sweden or Finland. Hagberg & Holmgren (2008) refers to a Finnish study, (Sokka, Koskela et al. 2005), and a Swedish, Uppenberg et. al. (2001). In most cases the peat is compared to the Finnish study. The Swedish study uses a combustion emission factor for CO_2 of 91 g/MJ and the Finnish uses 94.6 g/MJ. In Kirkinen et. al. 2007 the CO_2 emission factor is 92.2 g/MJ.

There are also emissions during the mining, processing and transportation of coal. These variations are also important to address because the variation can be great, particularly emissions of methane during the mining of coal. The emission factor for coal used in Hagberg & Holmgren (2008) takes the whole life-cycle into account. There are also great differences in the CH_4 emissions in for the mining, processing and fuel transport: 1.1 g/MJ in Swedish Uppenberg et. al. (2001) and 0.21 g/MJ in Finnish study (Sokka et. al. (2005). The difference is about 22 g CO_{2eq}/MJ using GWP_{100}. Kirkinen et. al. 2007 refers to an older Finnish study, Pingoud et. al. (1997) that estimates the emission factor for CH_4 to 0.34 g/MJ

The life-cycle emission factor for N_2O can almost be neglected (0.5 mg/MJ) in Sokka et. al. (2005) that is used in Kirkinen et. al. (2008) and partly in Hagberg & Holmgren (2008). In Uppenberg et. al. (2001) the emission factor is 24 times higher (12 mg/MJ), which used in Nilsson & Nilsson (2004) and some comparisons in Hagberg & Holmgren (2008). The difference adds approximately 3.5 g CO_{2eq}/MJ coal. The value used in Kirkinen et. al. (2007) is 2 mg/MJ and refers to Pingoud et. al. (1997).
The total life-cycle emission factor for coal is 125.3 g CO_{2eq}/MJ in Uppenberg et. al. (2001) and 104.1 g CO_{2eq}/MJ in Sokka et. al. (2005), both used in Hagberg & Holmgren (2008). The earlier version of Uppenberg et. al. (2001) with the same emission factor is used in

Nilsson & Nilsson (2004). Sokka et. al. (2005) is also used as reference in Kirkinen et. al. (2008). Kirkinen et. al. (2008) also presents an uncertainty span which shows that the highest value presented is not close to the 125.3 g CO_{2eq}/MJ used in Hagberg & Holmgren (2008) and Nilsson & Nilsson 2004. The emission factor in Kirkinen et. al. (2007) is 104.3 g CO_{2eq}/MJ coal, very close to values used in Kirkinen et. al. (2008). Väisänen et. al. (2013) ends up with a CO_{2eq} factor of 111 g/MJ which is high compared to the other Finnish studies but not close to the Swedish average used in Hagberg & Holmgren (2008). The source for this value is from the Ecoinvent database 2.0. The main reason that the coal emission factor in Uppenberg et. al. (2001) is much higher than in the other studies is the estimated CH_4 emission from coal mining of 1.1 g/MJ compared to 0.21 g/MJ in Sokka et. al. 2005.

The life-cycle emission factors for coal used in the reviewed studies are presented in Table 5.

Table 5. Life-cycle emission factors for coal used in the reviewed studies.

	Hagberg & Holmgren 2008	Kirkinen et. al. 2008	Kirkinen et. al. 2007	Nilsson & Nilsson 2004	Väisänen et. al. 2013
Coal	Two values used in the study; Uppenberg et. al. (2001) 125.3 and Sokka et. al. (2005) 104.1 g CO_2eq/MJ (Combustion emissions; Uppenberg et. al. (2001) 94.6, Sokka et. al. (2005) 94.8g CO_2eq/M)	Total LCA value: 104.1 g CO_2eq/MJ, same as Hagberg & Holmgren 2008, Sokka et. al. 2005. (Only combustion 94.8 g CO_{2eq}/MJ)	Total LCA value 104.3 g CO_2eq/MJ (Pingoud et. al. 1997) (only combustion 92.9 g/MJ)	Total LCA values; Swedish average 125.3 g CO_2eq/MJ, Only combustion 94.6 g/MJ Same as in Hagberg & Holmgren 2008	Total LCA value; 111 g CO_2eq/ MJ

5.3 Uncertainties and variations in results

The greatest uncertainties seem to originate from the input data (the measurements of fluxes to and from the particular peatland) and the assumptions made. Much of the uncertainties can be referred to the actual measurements of greenhouse gases to and from the peatland.

In the study by Holmgren et. al. (2006) a sensitivity analysis was made in order to show the variations in results depending on the variations in emission values (input data). An example of the results of the sensitivity analysis is presented in Figure 15 in order to illustrate the importance of input emission values (in this case the importance of the decomposing residual peat).

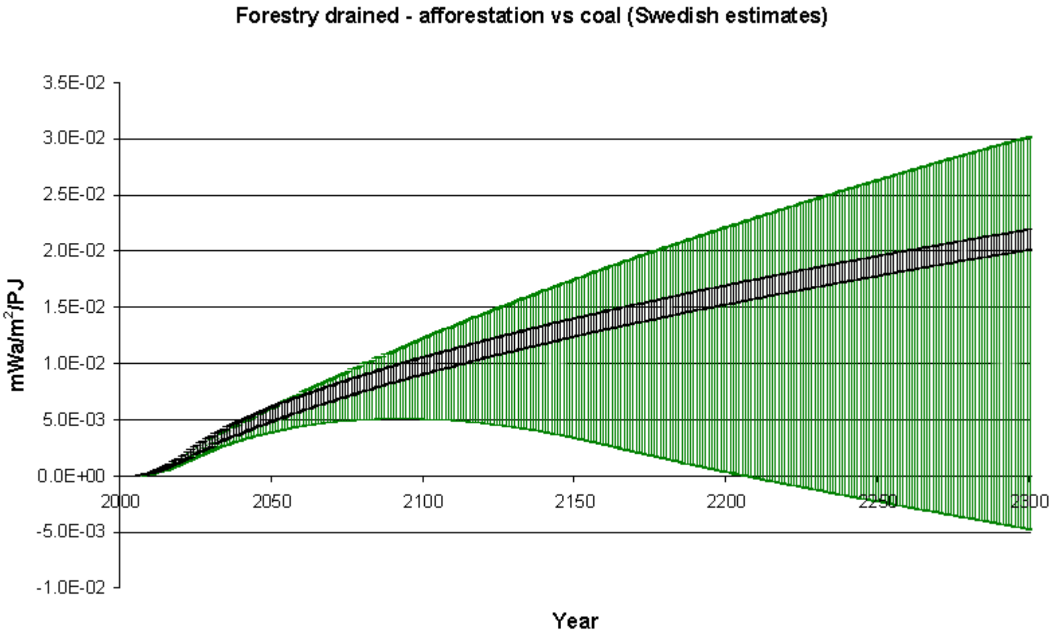

Figure 15. Scenario where forestry-drained peatland aftertreated by afforestation. The uncertainty ranges for both the peat-chain (green) and the coal-chain (black) are shown. The explanation for the uncertainty range of the peat-chain is due to different assumptions on the decomposition rate of the residual peat. From (Holmgren, Kirkinen et al. 2006).

As can be seen in the figure, the assumed decomposition rate of the residual peat layer will have a large impact on the final results; if residual peat decomposition is assumed to be small, peat will perform better than coal more or less instantly and if decomposition rate is assumed to be high peat will perform worse than the coal scenario Figure 15. The same principle is true for other assumptions such as the surrounding area or the carbon sequestration rate which both impact the results. The initial emissions from the type of peatland chosen for production will however be more important than the decomposition of residual peat.

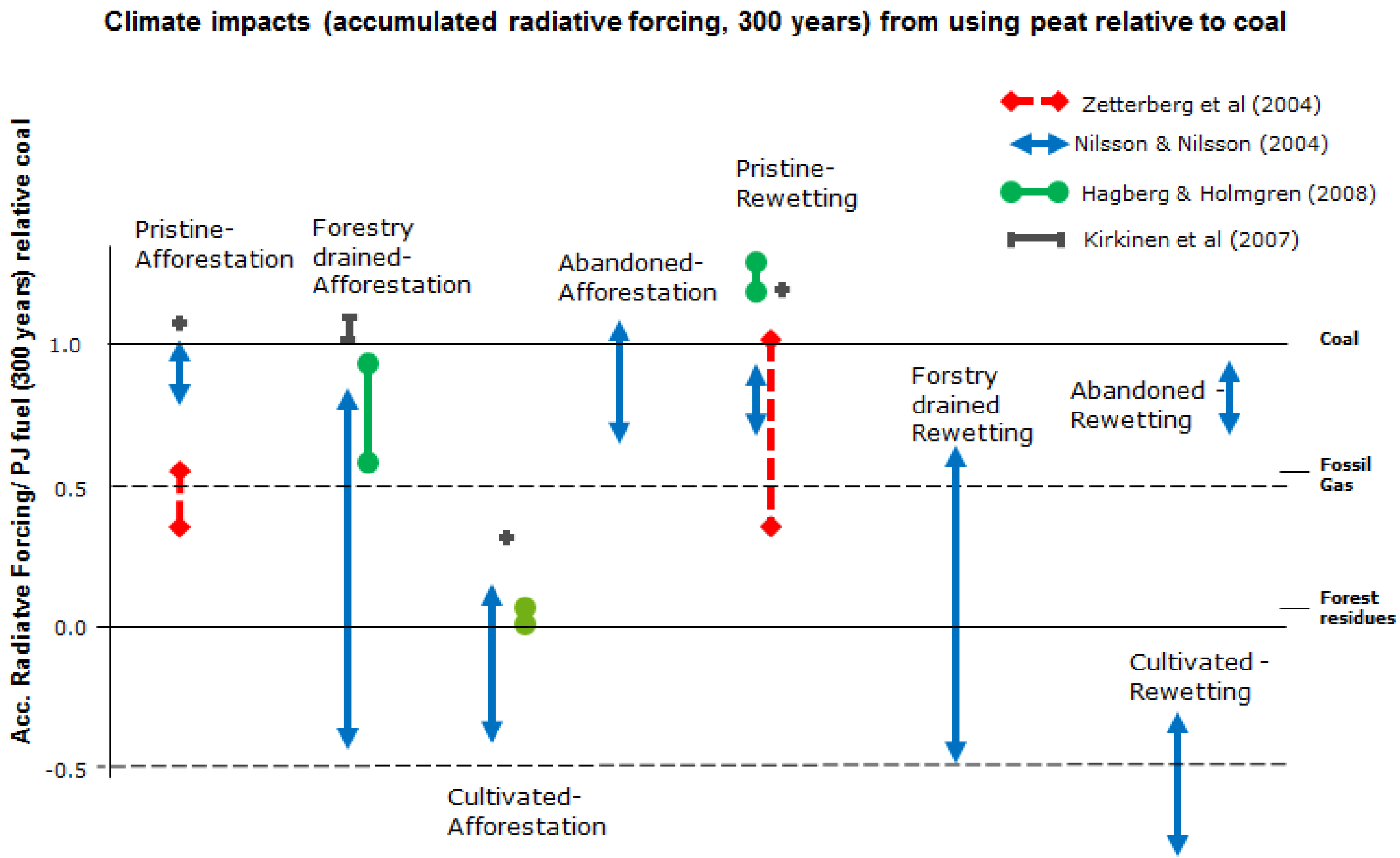

Figure 16. Variations in climate impacts from different energy peat utilisation scenarios relative to coal based on four studies. Values below zero indicate a positive impact on the climate (i.e. a climate cooling effect). Note that the climate impact from a 300 year perspective is highly uncertain. (Lars Zetterberg pers. com. 2013)

A summary illustration of the variations in results from different studies is highlighted in Figure 16 which summarizes radiative forcing results from four of the studies included in this review. Note that the time perspective here is 300 years. If a 100-year perspective would be used, most results would be closer to the emissions from coal (compare with the variations seen in Figure 16), but there would still be considerable variations. The illustration should therefore be used with caution since, as mentioned earlier, the uncertainties are greater the longer the time span. The main reasons to the differences in Figure 16 are different assumptions regarding primarily:

- Choice of peatland
    - High or low emitting peatlands
- Delimitations
    - Extraction time
    - Size of surrounding area and its peat depth
    - Production technology
    - Residual peat layer
    - Emission factors
    - Use of biomass from forested peatland
- After-treatment strategy
    - Forest growth rate
- Time span
- The reference system to which the results are compared

5.4 Climate impact of peat scenarios compared to coal scenario in a 100 year perspective

Väisänen et. al. (2013) is one of the studies that have a readable result for a 100 years perspective. In the study the peatlands are assumed to be a high emitting with afforestation as after-treatment method. Most sites were forestry drained and one site was cultivated croplands. Based on the assumptions made in Väisänen et. al. (2013) the results of the peat scenario gives approximately 35 % reduction compared to the coal utilization scenario, 72.7 g CO_{2eq}/MJ peat compared to 111 g/MJ for coal. Note that this is the only study that does not use radiative forcing to describe the climate impact. In Kirkinen et. al. (2008) the peat scenario for cultivated peatland with afforestation includes utilization of the trees for bioenergy purposes. In 100 years it is assumed that 82 % of the energy comes from the peat and 18 % from the trees. The reduction compared to coal is in this case approximately 40 %. For forestry drained and afforestation on the other hand the highest value for the coal scenario is approximately the same as the average for the peat scenario. In this case the final energy is 100 % peat. In Hagberg & Holmgren (2008) the peat scenario with cultivated peatland and afforestation gives approximately 33-55 % reduction compared to the coal scenario. The highest reduction is achieved from the scenario with new peat milling techniques. Looking at forestry drained sites and afforestation the peat scenarios give in most cases a lower climate effect than the coal scenario. Cases including the new milling method are in general better than the coal utilization scenario while the ones including conventional milling method are about the same as coal. In Nilsson & Nilsson (2004) there are many scenarios for cultivated peat land depending on the former use of the peat land.

Two relevant peat scenarios for each of the reviewed reports are compared with coal in Table 6 and Table 7. One is a scenario with cultivated peatland (former land use is grass and barley respectively. In the mentioned peat scenarios the climate impact reduction is 45-65 % compared to the coal scenario using a tree growth rate of 7.5 m^3/ha/y (highest reduction for land use for growing barley)

Table 6. The reduction of climate impact compared to the coal utilization scenario for the different reviewed LCA studies. The peat scenario chosen in this case is forestry drained peat lands with afforestation.

Hagberg & Holmgren 2008	Kirkinen et. al. 2008	Kirkinen et. al. 2007	Nilsson & Nilsson 2004	Väisänen et. al. 2013
Peat extracted with **new production method show a lower result than coal while the milling method gives about the same result as the coal** utilization scenario. (Converting radiative forcing to GWP_{100} shows that results vary approximately between 50-120 g CO_{2eq}/MJ). This would on average be a reduction of 23 % *(Diagram readings)*	**Approximately the same climate impact as coal**. The peat and coal scenarios overlap each other. Highest value for coal scenario is in same level as the average value for the peat utilization scenario. *(Diagram readings)*	**Almost same climate impact** as the coal utilization scenario. *(Diagram readings)*	Includes nine different scenarios were **most peat scenarios show lower climate impact than coal**. For example from site with relative low productive conifer forest before extraction and afforestation with a growth rate of 7.5 $m^3\ ha^{-1}\ a^{-1}$ have approximately **30 % reduction** compared to the coal utilization scenario *(Table and diagram values)*	**35% reduction** compared to the coal utilization scenario. Most sites included are forestry drained.*(Numerical values in text)*

Table 7. The reduction of climate impact compared to the coal utilization scenario for the different reviewed LCA studies. The peat scenario chosen in this case is high emitting cultivated peat land and afforestation.

Hagberg & Holmgren 2008	**Kirkinen et. al. 2008**	**Kirkinen et. al. 2007**	**Nilsson & Nilsson 2004**	**Väisänen et. al. 2013[2]**
33-55 % reduction compared to coal scenario. Highest reduction for the scenario with the new method. *(numerical values in text)*	Approximately **40 % reduction**. Note that the scenario includes the use of trees from the after treatment as bioenergy. In 100 years 18 % of the total energy extraction is assumed to be bioenergy (*Diagram readings)*	Approximately **20 % reduction** compared to the coal utilization scenario (*Diagram readings)*	**45-65 % reduction** compared to the coal scenario. 65 % reduction if land is used for growing barley and 45 % if it were a grassland *(Table and diagram values)*	**35 % reduction** compared to the coal utilization scenario. *(Numerical values in text*

6 Conclusions

This report has reviewed recent LCA studies of energy peat including variations in the underlying data on emissions from peatlands. Life-cycle analyses can estimate the climate impact from energy peat and can act as a tool for making sound decisions concerning peat extraction activities. It is important to note though that life-cycle analyses are uncertain and highly dependent on assumptions made during the different stages of the life-cycle. For energy peat the uncertainties are mainly related to the choice of peatland, the assumptions made regarding extraction time, surrounding area, the residual peat layer and after-treatment strategy.

The review in this study shows that different studies have come to different conclusions on the climate impact from energy peat. The studies reviewed also show that the climate impact can be reduced by making the right choices during peat extraction.

Four factors are especially important for the climate impact from energy peat utilization:

- By choosing high-emitting peatlands for production and extracting peat in the most efficient way the climate impact from energy peat can be significantly decreased compared to coal.

[2] Note that this scenario includes mostly forestry drained sites

- Most important factors for the climate impact are initial peatland type, after-treatment strategy and energy peat production technology.
- A life-cycle perspective is needed when looking at the climate impact from energy peat.
- To fully account for the climate impact of energy peat the time perspective is of major importance.

According to this study a life-cycle perspective is needed in order to understand the total emissions and uptakes that occur throughout the peat utilization chain. Combustion emissions are just one part of the total life-cycle emissions.

The effects of co-combustion were not included in this study. Based on available research it seems clear that co-combustion of peat and wood-fuels can have positive effects such as lower maintenance of boilers and higher efficiency which in turn can lead to lower emissions.

In order to better understand the climate impact of energy peat there is a need for more research on how different peatland types can be evaluated from a climate point of view. Even with more knowledge there will still be uncertainties in emissions from peatlands, but the possibility to choose the most suitable areas for extraction would be better.

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Appendices: Relative cover of peat soils in EU-27 countries

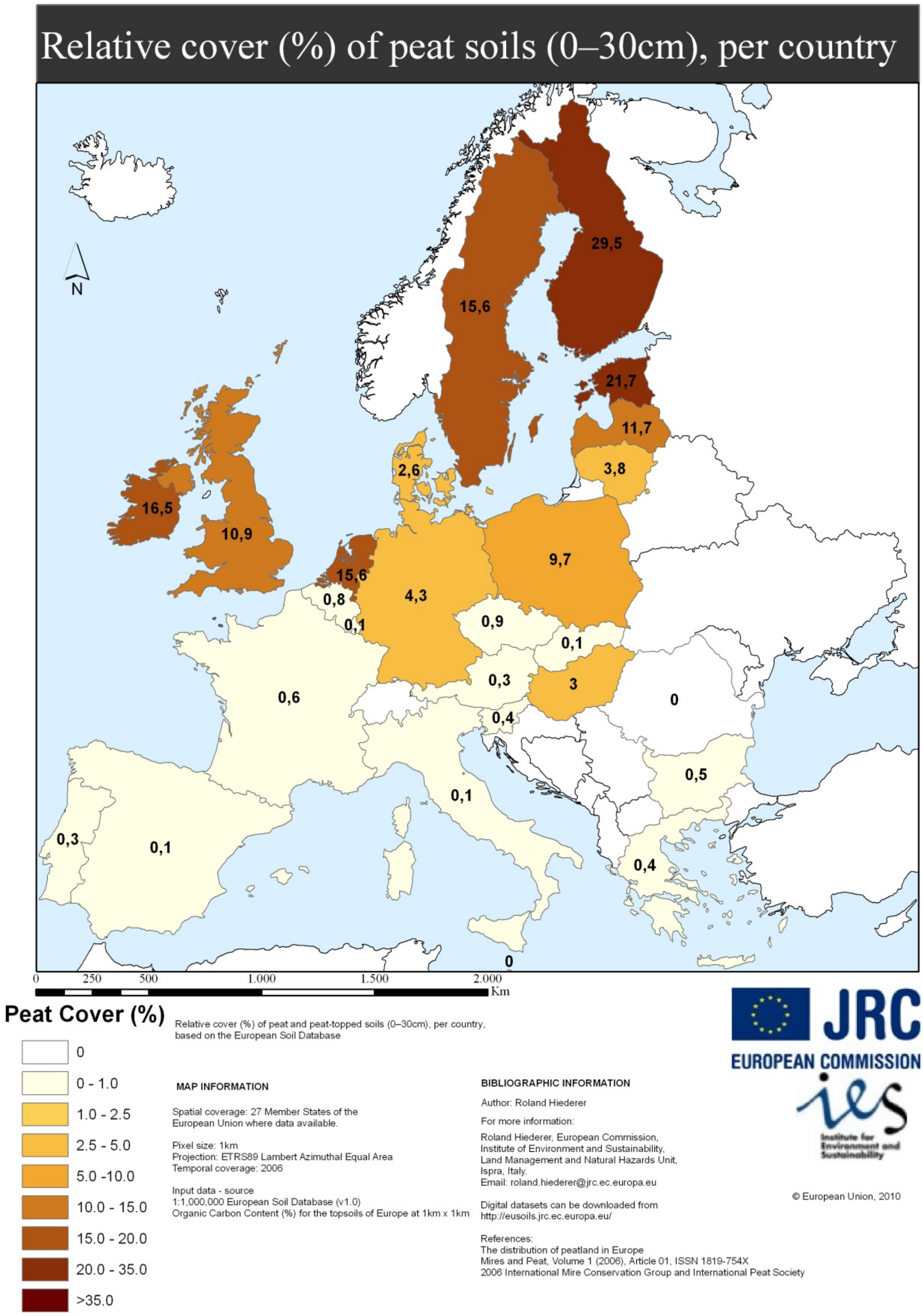

Figure 17: Map of relative cover of peat soils 0-30 cm per Country Europe (Montanarella, Jones et al. 2006)