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Foreword

Peat is a domestic fuel of national importance to Finland and, considering its employment impact, it also has regional policy significance. On the basis of the National Climate Strategy (VNS 1/2001 vp), the Ministry of Trade and Industry commissioned in January 2001 a survey of the needs for further research into the life cycle analysis of peat. The purpose of the survey was to estimate what information will be needed to scientifically motivate, if possible, the introduction of calculation methods which better take into account the life cycle of peat in calculating emissions from the use of peat under the principles of the Kyoto Protocol. Another motivating factor was Finland's obligation to report on emissions from peat and peatlands under the United Nations Framework Convention on Climate Change (UNFCCC), the aim being to further specify these values.

As a result of the survey, an extensive research programme entitled *Greenhouse Impacts of the Use of Peat and Peatlands in Finland* was launched. Since the four-year programme, by its nature, required extensive resources for conducting measurements in the field, it was jointly funded and steered by the Ministry of Trade and Industry, the Ministry of Agriculture and Forestry and the Ministry of the Environment. The programme consisted of several research projects whose purpose was to establish the greenhouse gas (GHG) balances of peatlands in various types of land use. The practical work involved was carried out by research teams at three universities and four research institutions: the Universities of Helsinki, Joensuu and Kuopio, the Finnish Forest Research Institute (Metla), the Finnish Meteorological Institute, the Geological Survey of Finland and VTT Technical Research Centre of Finland.

The results of the programme have already contributed to a significant specification of the emission factors of the greenhouse impacts of peatland land use for the national GHG inventory, and life cycle analyses have been employed to establish peat utilization models that would minimize the greenhouse impact of peat use.

It was partly due to the findings of this programme that the classification of peat in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories was changed to recognize peat as a class of its own between fossil fuels and biomass. In the greenhouse gas inventory, however, the emission calculations in the energy sector are only based on emissions generated through combustion. Life cycle emissions analyses cannot be applied in the reporting of greenhouse gas emissions under the Kyoto Protocol.

Parkano, 28 September 2007

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Summary

Background and needs for information

Pristine peatlands are carbon accumulating ecosystems. Since the last Ice Age, the Finnish peatlands are estimated to have accumulated some 5.4 billion tonnes of carbon, forming the largest soil carbon stock. From the original 10 million peatland hectares ~5.7 million ha have been drained for forestry and ~0.7 million ha for agriculture. The area used for harvesting of energy and environmental peat is ~60,000 ha. Circa 40% of the original peatland area still remains in a natural state.

Peat combustion covers 5 to 6 per cent of Finland's total energy requirements. Peat is a nationally important fuel for Finland; with the employment aspects, it also has regional political importance. In the international statistics (OECD/IEA/Eurostat) peat is paralleled with fossil fuels. In Finland peat is classified as slowly renewing biomass fuel, the time required for the peat layer to rebuild being very long. In the **National Climate Strategy** published in 2001 (VNS 1/2001 vp), it was noted that "peat is left for the national authorities to decide upon and thus outside the scope of the EC Directives on energy taxation. **In international statistical practice, it is supported that peat would be separated from the fossil fuel category to form a category of its own.**" It was also noted: "As far as the [United Nations Framework] Convention on Climate Change and other international cooperation are concerned, the following action will be taken:

- The need for supplementary studies will be mapped out in a survey and a research programme will be launched based on this survey for a life cycle analysis of the energy use of peat.
- If it is justified on the basis of the research findings, measures will be undertaken to influence the rules and definitions of the methodology used for calculating greenhouse gases by virtue of the international Convention on Climate Change. In this, the aim will be that the calculation methods subject to the Convention would take the greenhouse gas balance of peat into account during the entire life cycle and not just the emissions from combustion.
- To be able to influence the Convention on Climate Change, clear criteria, besides new research data, will be required for the energy use of peat. The criteria shall state e.g. the definition of those peatlands on which the production of energy peat will be directed, as well as the requirements for subsequent use of the peat production areas."

Related to the preparation of the Climate Strategy, the Ministry of Trade and Industry commissioned in January 2001 a survey of the need for further research into the life cycle analysis on peat. The purpose of the survey was to estimate what information will be needed to scientifically motivate, if possible, the introduction of calculation methods better taking into account the life cycle of peat in calculating emissions from the use of peat under the principles of the Kyoto Protocol.

Another motivating factor was Finland's obligation to report on emissions from peat and peatlands under the United Nations Framework Convention on Climate Change (UNFCCC), the aim being to further specify these values.

As a result of the survey (Minkkinen & Laine 2001), a four-year research programme (2002–2005) was set up, jointly funded by the Ministry of Trade and Industry, the Ministry of Agriculture and Forestry and the Ministry of the Environment. Its principal purpose was to assess the levels of greenhouse gas emissions from the use of peat and peatlands in Finland.

Research programme: Greenhouse Impacts of the Use of Peat and Peatlands in Finland 2002–2005

The programme consisted of nine separate research projects under a coordination project; some were 'method projects' and others involved a specific sector of land use.

The purpose of the programme projects was to draw up models (dynamic emission factors) for the greenhouse gas (GHG) balances of peatlands subject to different kinds of land use and to quantify the underlying ecosystem processes. The scientific findings of these projects have been reported in a special issue of the journal Boreal Environment Research, which can be found at: http://www.borenv.net.

The emission factors developed in the programme have already been used in Finland's new national GHG emission calculations, the annual inventory reports submitted under the United Nations Framework Convention on Climate Change (UNFCCC), and the Kyoto Test Report in 2007.

The newest information produced by the programme was also used as source material for the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, adopted at the IPCC session on Mauritius in April 2006. It was partly due to the findings of this programme that the classification of peat in the IPCC 2006 guidelines in the emission source class 'energy' was changed in order that peat is now classified as a class of its own between fossil energy sources and biomass. In this reporting, however, the emission calculations are only based on emissions generated through combustion. Life cycle emissions analyses cannot be used for reporting under the Kyoto Protocol.

The emission factors calculated for various classes of land use are based on measurements conducted in different parts of Finland over several years.

Use of peatlands and greenhouse gas balances

Out of Finland's original 10 million hectares of peatlands circa 5.4 million ha has been drained for forestry and circa 0.7 million ha for agriculture. This leaves some 4 million hectares in a pristine state. The largest part of the area used for fuel peat production has already been drained for forestry, but also pristine peatlands have been used for peat production. By contrast, peatlands formerly drained for agriculture are rarely used for harvesting peat because of the problems involved in the traditional production method. **From the perspective of climate impact, it naturally makes sense to locate peat production in areas where anthropogenic greenhouse gas emissions are high, so that in the overall greenhouse gas balance the cessation of those emissions because of fuel peat harvesting will compensate for some of the greenhouse impact created by the combustion of that peat. Similarly, further use of areas no longer used for peat production must be planned so that at the life cycle level the greenhouse impact of the use of those areas is as low as possible.**

Greenhouse gas balances of pristine peatlands as a background to the impact of the use of peatlands and peat

This research programme focused on the carbon balance of pristine, i.e. undrained, peatlands by measuring carbon dioxide (CO_2) and methane (CH_4) exchange at the ecosystem-atmosphere boundary of both raised bogs and sedge fens. The balance for these two carbon-containing gases constitutes the majority of the carbon balance of a peatland. In photosynthesis, CO_2 is bound into plant biomass. Decomposition releases most of the bound CO_2 back into the atmosphere. Anaerobic decomposition also generates CH_4, some of which is emitted into the atmosphere. CH_4 has a GWP factor (Global Warming Potential, IPCC) about 20 times higher than that of CO_2 when emissions are considered over a 100-year period.

The gas exchange and the resulting annual carbon balance are sensitive to varying weather conditions. The annual carbon dioxide balance of a sedge fen can vary from a net release of over 1,000 kg per hectare to nearly an equal net sink. Similarly, on raised bogs the annual CO_2 balance was found to fluctuate between an emission of 850 kg/ha per year to an accumulation of 670 kg/ha per year. CH_4 emissions vary between <15 and 530 kg/ha per year on sedge fens (minerotrophic peatlands) and between <15 and 200 kg/ha per year on raised bogs (ombrotrophic peatlands). Wetness slows down decomposition so much that over a long period of time some of the dead plant biomass turns into peat. On average, Finland's sedge fens and raised bogs have accumulated 170 kg/ha and 210 kg/ha of carbon per year, respectively, since the last Ice Age. The increased occurrence of summer droughts causes water level lowering also in peatlands. In these conditions the organic matter that has been stored during the previous decades is exposed for aerated conditions above the water level and the rate of oxidation increases, causing an annual net loss of peat. Many observations in drought situations support such losses of peat in both fens and bogs.

Forestry is the most important form of land use for peatlands

Previous research results show that the soil of forestry-drained peatlands is a significant carbon sink, but the results from modelling simulations carried out in this research programme indicate the opposite. According to these results, the soil carbon balance of Finnish forestry-drained peatlands is, on average, negative. Instead, the carbon uptake of the growing tree stand may exceed the soil emissions. The simulations so far contain high uncertainty and the recently initiated supplementary studies will confirm the results in the coming years.

In the forestry-drained areas the aerobic decomposition of the old organic matter of the soil (peat and humus) to carbon dioxide constitutes the largest release/removal in the carbon balance of peatland forests. Based on the estimation, this carbon dioxide (CO_2) emission is annually 6,050–16,900 kg of carbon per hectare, depending on the nutrient status of the peatland. The emission is the largest in nutrient-rich sites and smallest in the nutrient-poor drainage areas. Most of our peatland forests grow in the nutrient-poor and intermediate peatland site types. The simulated average annual emission from these site types is 7,700–10,600 kg/ha of carbon. In addition, carbon is released in leaching as dissolved organic carbon, which counts annually some 60 to 100 kg/ha, and in the possible forest/peat fires. Part of the released carbon is replaced by the litter production of the tree stand and forest vegetation, which feeds new organic matter above the ground and into the soil (peat). For this reason the total carbon balance of a certain site may be positive or negative (Table 1).

When water level is high, methane (CH_4) is produced in drained sites, as well; however, the measured annual methane emissions in sparsely forested nutrient-poor sites are, at most, less than 30 kg of methane per hectare. The effectively drained areas are commonly weak methane sinks, where the annual methane consumption from the atmosphere remains less than 7.5 kg per hectare. **Significant amount of nitrous oxide (N_2O) is released only from the nutrient-rich or nitrogen fertilized peatland forests. Nitrous oxide is released in small amounts (on average ~2 kg per hectare per year), however, due to its large greenhouse impact (~300 times CO_2) this emission source may be significant for the total emission of drained peatlands.** The ongoing supplementary studies will improve the estimate in the near future.

More reliable emission factors for peat harvesting areas through new measurements in the present study

Most of the gas emissions measured were of the same magnitude as the few earlier findings, but there were some surprises, too. In especially warm and humid conditions, a milled peat field may emit up to five times the normal amount of carbon dioxide (CO_2) (40,300 kg/ha per year as opposed to the average of 9,400 kg/ha per year). The storage of harvested peat in the stockpiles may double the carbon

Table 1. An example of the composition of the soil carbon dioxide balance in forestry-drained peatlands with different nutrient status. Negative values indicate net release from the ecosystem into the atmosphere.

	Litter production g C m^{-2} a^{-1}	Decomposition of peat and litter	Soil C balance
Intermediate peatland	500 [1,834 g CO_2]	–572 [2,099 g CO_2]	–72 [264 g CO_2]
Nutrient-poor peatland	496 [1,818 g CO_2]	–491 [1,799 g CO_2]	+5 [+18 g CO_2]

The conversion factor C => CO_2 is 3.667

dioxide emissions of milled peat fields, if the annual area of the stockpiles is assumed to be 10% of the peat harvesting area. The peat harvesting fields release methane at moderate rates (3–90 kg/ha per year) and nitrous oxide at weak rates (2–5 kg/ha per year).

New research confirms and specifies data on significant carbon dioxide and nitrous oxide emissions from peatlands used in agriculture

The emission ranges shown below come from new, measurement-based studies. The nitrous oxide (N_2O) emissions are due not only to peat being naturally rich in carbon and nitrogen but also to the nitrogen content of fertilizers. Although the emission levels are sensitive to weather conditions, only a small portion of the emissions can actually be predicted on the basis of the weather. An uncertainty factor must be added to any emission estimates, and this broadens the range of variation considerably, particularly for N_2O (Table 2).

CO_2 emissions from organic cropland, whether ploughed land or covered by vegetation, are roughly the same, being 25,300 to 40,300 kg/ha per year on ploughed land, 2900 to 27500 kg/ha per year in grass cultivation and 7700 to 30400 kg/ha per year on a grain field. N_2O emissions from organic cropland that is ploughed are 6 to 58 kg/ha per year, typically higher than for organic cropland covered by vegetation (2 to 37 kg/ha per year in measurements in recent years). Recent studies show that anything from 25% up to 60% of all N_2O emissions occur in the winter. Organic cropland is a weak methane (CH_4) sink, because the water table is quite far from the surface. When the peat gets wet and its oxygen content decreases, organic cropland only generates slight emissions. On organic cropland where cultivation has been abandoned, gas emissions would seem to stay at approximately the same level for decades afterwards.

Afforestation of organic cropland and cutaway peatland has been estimated to reduce greenhouse impact, and new findings seem to support this projection

The findings do show, however, that **emissions from the soil do not decrease so much that the amount of carbon bound by the trees at the site would be enough to make the overall carbon balance positive.** Decomposition of peat and old litter caused annual emissions of carbon dioxide (CO_2) of between 10,100 and 17,600 kg per hectare per year in afforested cutaway peatland and between 7,600 and 19,800 kg per hectare per year in afforested organic cropland (Table 3), which is similar to or greater than emissions in forestry-drained peatland but clearly less than emissions in organic cropland that is not afforested. When the CO_2 absorbed annually by trees is subtracted from the CO_2 emissions from the soil, assuming the CO_2 absorption due to annual growth to be between 1,650 and 12,100 kg/ha per year, the CO_2 balance for the entire ecosystem probably remains negative in the majority of cases. These figures do not include the carbon bound in the surface vegetation and accumulating litter, but

Table 2. Annual greenhouse gas (GHG) emissions from organic cropland. The minimum and maximum values represent actual observed values for each cultivation type. Negative values indicate a net influx of the substance from the atmosphere into the ecosystem.

GHG	Average cropland	Grass	Cereal	Fallow	Abandoned
CO_2, g m^{-2} a^{-1}					
Average	2,072	1,485	1,760	2,971	1,188
Min–Max	290–4,033			2,167–4,033	–330–3,300
CH_4, g m^{-2} a^{-1}					
Average	0.42	1.27	–0.43	0.41	–0.22
Min–Max	–0.49–0.91	0.11–0.91	–0.49–0.51	–0.35–4.00	
N_2O, g m^{-2} a^{-1}					
Average	1.74	0.85	1.74	2.63	1.29
Min–Max	0.17–5.81	0.17–1.56	0.85–3.79	0.60–5.81	

Table 3. Annual greenhouse gas (GHG) emissions due to decomposition of organic matter in the soil in afforested organic cropland and cutaway peatland. Negative figures indicate a net influx of the substance in question from the atmosphere into the ecosystem. NB: In order to calculate the carbon dioxide (CO_2) balance of the soil and the ecosystem as a whole, the carbon bound in the trees and litter in the area must be subtracted from the emissions. Tree species and site type affect the amount of uptake.

GHG	Afforested organic cropland	Afforested cutaway peatland
CO_2, g m^{-2} a^{-1}		
Average	1,354	1,397
Min–Max	759–1,976	1,008–1,756
CH_4, g m^{-2} a^{-1}		
Average	–0.15	–0.05
Min–Max	–0.43–0.81	–0.03–0.09
N_2O, g m^{-2} a^{-1}		
Average	1.02	0.15
Min–Max	0.16–4.71	0.02–0.75

micro-meteorological measurements on an afforested cropland confirm the estimate that afforested cropland remains a small source of CO_2 (about 500 kg/ha per year). Afforestation does slow down CO_2 emissions for a few decades, i.e. for the period during which the trees and underground biomass are growing. **However, both afforested cutaway peatland and afforested organic cropland would seem to continue emitting nitrous oxide (N_2O).** Even when afforested, organic cropland was found to emit more N_2O (2 to 47 kg/ha per year) than cutaway peatland (0.2 to 7.5 kg/ha per year).

Restoration of cutaway peatland as an after-use of peat harvesting binds carbon dioxide into long-term stock

Restoration also causes methane (CH_4) emissions to recur as the peatland evolves. Restored areas begin to show a net influx of carbon within a few years of the return of peatland vegetation. Under favourable conditions, carbon may be absorbed very quickly, particularly because photosynthesis is efficient and little CH_4 is emitted due to anaerobic decomposition. The most important factor for the success of restoration is sufficient moisture.

CH_4 emissions follow the binding of new organic matter with a delay. At the beginning of the restoration process, for several years, CH_4 emissions from the former cutaway peatland can be lower than those from pristine sedge fens. However, an area accumulating new plant biomass exceptionally fast can under suitable circumstances generate CH_4 emissions up to over 400 kg/ha per year. Over time, carbon dioxide (CO_2) sequestration may slow down, and the CH_4 release processes become stable so that the carbon gas fluxes in restored peatlands come to match those of pristine peatlands.

The findings concerning the gas balances in pristine peatlands on the land uplift coast in Siikajoki (on the coast of the Gulf of Bothnia) support the conclusions drawn regarding restoration sites. Studies of wetlands of different ages in Siikajoki, from shore swamps 100 years old to Sphagnum bogs 2,500 years old, show that photosynthesis was at its most efficient in the younger areas and slowed down as the age of the peatland increased. CH_4 dynamics were also the most unstable in younger areas, whereas the oldest peatlands were steady sources of CH_4. The paludification process in pristine peatlands was much slower than in human-regulated restored cutaway peatlands, where the occasional dry spell did not hinder development. **After the re-establishment of stabilised peatland vegetation, restored cutaway peatland functions just like a pristine peatland.** Because there is a strong correlation between carbon absorption and peatland vegetation, vegetation could be used as a simple indicator for evaluating the carbon balance and CH_4 emissions of restored cutaway peatland. Unlike pristine peatlands, restored cutaway peatland forms part of the land use categories to be reported in greenhouse gas inventories, even though the purpose of land use in these areas is to remove the anthropogenic impact and to return them to their natural state. **Indeed, there is a case for considering restoration as a temporary form of land use for returning an area to the state in which it was before human intervention, which means that a restored peatland could be excluded from the greenhouse gas inventory after a specified period of time, just like pristine, undrained peatlands.**

Greenhouse impacts of using peat for energy, from the life cycle perspective

Peat is a fuel of national importance in Finland, but using peat for energy causes greenhouse gas emissions. These emissions have grown with the increasing use of fuel peat. All Parties are required to make an inventory of greenhouse gas emissions and to report on it to the UNFCCC. Finland's greenhouse gas inventory and emissions trading equate peat with fossil fuels for the purpose of calculating emissions, in accordance with the IPCC Guidelines, although under the 2006 Guidelines peat is to be reported in a class of its own, separate from fossil fuels. With the progress of emissions trading, peat production is expected to decrease, especially in the generation of condensing electricity.

The purpose of the greenhouse gas inventory under the UNFCCC is to present anthropogenic greenhouse gas emissions and sinks during the report year as accurately as possible. This enables monitoring of actual trends in greenhouse gases and assessment of meeting the commitments under the Kyoto Protocol, among other things.

Life cycle assessment of greenhouse impacts differs from the greenhouse gas inventory in that it takes into account all the significant emissions and sinks caused by the product in question. For an ordinary product, emissions are generated within a relatively short period of time. In the case of peat fuel, however, the time dimension introduced by the after-use of the cutaway peatland (e.g. restoration, afforestation or cultivation) may be defined in anything up to centuries in terms of emissions and sinks. Because life cycle assessment takes into account emissions and sinks that may exist in the remote future, its results are not compatible with the inventory approach, which only takes into account the actual emissions and sinks of the report year. In addition, in the greenhouse gas inventory the emissions are reported by land use sectors and emission classes. Here the emissions during the life cycle of one function, such as the energy use of peat, are placed in several emission classes (for example, combustion, harvesting machines and subsequent use of the peat harvesting area).

This present research programme considered the greenhouse impacts of the use of peat for energy from the life cycle assessment perspective. The greenhouse impact is estimated using radiative forcing, which describes the perturbation to the Earth's radiative energy balance caused by greenhouse gases and leading to climate change.

The peat-energy production chain consists of fuel peat harvesting in various production areas, generating energy by peat combustion, and after-use of the production areas. The studies considered various types of peat harvesting area: pristine peatland (fens), forestry-drained peatland and organic cropland. After the peat harvesting, the subsequent land use forms of the cutaway areas were peatland restoration, afforestation and cultivation of reed canary grass (*Phalaris arundinacea*). Several different peat fuel production chains were created using these options of initial states and after-use. In this study, the use of peatland was examined from two perspectives: the production chain was restricted to peat only, or secondly, renewable energy (wood biomass, reed canary grass) grown in the harvesting area was also considered.

In the research project, the greenhouse impacts of the various fuel peat production chains were simulated over a period of 300 years. The production chain is delimited to apply to peat energy only. In order to limit the increase of the average temperature of the Earth to two or three degrees (the European Union has proposed 2 °C), the world's greenhouse gas emissions must be reduced significantly in the course of the present century. Therefore, a time horizon of 100 years may be considered significant in assessing the greenhouse impacts of various fuels. **The greenhouse impact of using a pristine sedge fen for fuel peat production is similar or even greater than that of coal** (chains 1–2). This is due, among other things, to the ceasing of carbon sequestration when the peatland is prepared for harvesting. A uniform method is used for assessing the greenhouse impacts of coal and peat, and the results are comparable. **Using forestry-drained peatland for fuel peat production (chain 3) also causes a slightly greater greenhouse impact than coal, unless the peat is harvested with sufficient precision. Harvesting residual peat as precisely as possible to recover its energy potential brings the greenhouse impact of this chain to the same level with that of coal.**

With modern technology, the most climate-friendly peat energy production chain is the one using peatland which is or has been in agricultural use (organic cropland) and which is afforested once peat harvesting is finished (chain 4). Taking organic cropland over for peat harvesting discontinues the major emissions associated with its agricultural use, making this chain beneficial for the climate.

Using high-emission peatlands (such as organic cropland) for peat harvesting and employing new technology can keep the greenhouse impact of the energy use of peat somewhat lower than that of coal when assessed over a 100-year time horizon.

In this study also the so called 'vision chains' were examined, to show the lowest possible level of greenhouse impact from peat production. This can be achieved by minimizing emissions in different steps of the chain by using modern technology. In vision chain A peat is harvested from forestry-drained peatland. In vision chain B peat harvesting is located in areas that are major sources of greenhouse gas emissions prior to this harvesting (organic cropland). The modern technology employed includes improved combustion especially with regard to nitrous oxide (N_2O) emissions and new peat harvesting technology aiming at shorter production times and lower emissions from the peat field and stockpiles. In vision chain A, where the harvesting area is forestry-drained peatland, the greenhouse impact is lower than that of coal. In vision chain B, the greenhouse impact begins to decline after only 100 years and almost achieves neutrality in 300 years.

Using cutaway peatland for producing renewable bioenergy and partial mixed fuel combustion can significantly reduce greenhouse impact

Using peatland for both peat harvesting and producing renewable bioenergy has also been studied. Included in the study were the production chains where the peat harvesting area is used not only for producing fuel peat but also for producing renewable energy in the long term (reed canary grass or wood biomass) after peat harvesting is ended. The production areas studied are cultivated peatland (organic cropland) and forestry-drained peatland. The study time horizons are 100 and 300 years from the start of the production. Renewable energy production brings down the relative impact of the use of peat for energy. In the long term, especially using peat from organic cropland together with biomass decreases the greenhouse impact to a fraction of that of coal. New technology in fuel peat production further decreases the greenhouse impact.

The greenhouse impact of peat has been studied in Sweden as well. A review of earlier Finnish and Swedish studies showed that their findings were largely in agreement but that there were also differences. Because of this, a study was conducted on the similarities and differences between the most recent Finnish and Swedish research. The greenhouse impact of peat has not been studied in any other country, and for this reason it is important to find out what causes the differences in the assessments and baseline values. A comparative study showed that the scientific approach and calculation method are very similar in both the Finnish and Swedish studies. The main difference was in the input values, particularly in the case of emissions from forestry-drained peatlands.

Conclusions

- The research programme contributed substantially to the knowledge about the impact of land use on the greenhouse gas balance of Finland's peatlands, and in some respects existing conceptions about greenhouse gas emissions were significantly revised.
  - The carbon dioxide balance of forestry-drained peatland used to be considered positive, but the new findings show that on average it is negative (forestry drained peatland looses carbon).
  - By contrast, existing data on substantial emissions of carbon dioxide and nitrous oxide from current or former organic cropland were confirmed by the new findings.
  - It was somewhat surprising to note that afforestation of organic cropland is not enough to render the overall greenhouse gas balance positive, although it does reduce emissions.

- The purpose of the greenhouse gas inventory under the UNFCCC is to report as accurately as possible the actual anthropogenic greenhouse gas emissions and sinks during the report year. This enables, inter alia, monitoring of true development of greenhouse gases and assessment of meeting the commitments under the Kyoto Protocol.

- Life cycle assessment of greenhouse impacts differs from the greenhouse gas inventory in that it takes into account all the significant emissions and sinks caused by the product in question. The present research programme concerned the greenhouse impacts of the use of peat for energy from the life cycle assessment perspective.

- With present methods, the use of peat for energy causes a greenhouse impact of similar magnitude as the use of coal. The results, however, include uncertainty partly due to the long integration periods considered, and partly due to the unknown distribution of the initial state emissions of the former forestry-drained peatlands which currently are under peat production. Taking into account the use of peatland for renewable bioenergy production after peat harvesting is finished, the greenhouse impact of the overall energy use of peatland is less than that of coal.

- The greenhouse impact of peat can further be significantly reduced by directing peat harvesting to current or former organic cropland and to those forestry-drained areas which have high emissions in their current state. In these cases, the greenhouse impact decreases significantly in the long term.

- The greenhouse impact of peat energy can be decreased by thorough utilization of residual peat, improvement of combustion techniques, and with new peat harvesting methods. The production of renewable bioenergy in the areas available after peat harvesting will decrease the greenhouse impact per total produced energy unit. Afforestation is slightly more climate-friendly as an after-use measure for cutaway peatland than restoration. Cultivation of reed canary grass has roughly the same effect as afforestation with regard to the greenhouse impact.

- Peatland restoration aims at removing human impact and restoring the natural condition. Indeed, there is a case for considering restoration as a temporary form of land use for returning an area to the state in which it was before human intervention. Accordingly, restored peatlands could be removed from greenhouse gas inventories, corresponding to pristine peatlands, after a certain time period.

- Knowledge of the greenhouse impact of land use in peatlands is still fragmented and largely deficient. More research is needed particularly on the net exchange of carbon dioxide (soil carbon balance) of forested peatlands in different peatland site types from the southern and northern parts of Finland and on nitrous oxide balances on nutrient-rich peatlands, especially organic croplands. The knowledge on greenhouse gas balances of cut-away peatlands after peat harvesting and from the different after-use options is still meagre, since there are only few such areas at present. The proportion of these areas will increase considerably in the future, however, and more research should be conducted.

Greenhouse Impacts of the Use of Peat and Peatland in Finland

1. Background and aims of the research programme

Pristine peatlands are ecosystems which act as carbon sinks. It is estimated that Finland's peatlands have absorbed some 5.7 billion tonnes of carbon since the last Ice Age, constituting the largest natural carbon stock in Finnish soil. Finland originally had nearly 10 million hectares of peatlands, of which c. 5.4 million ha have been drained for forestry and c. 0.7 million ha for agriculture. Some 60,000 ha are used for harvesting fuel peat and environmental peat. This leaves c. 40% of the original peatland area still in a natural state. Most of the land now used for harvesting fuel peat (peat burned to generate energy) was formerly forestry-drained, but some pristine peatlands have also been taken over for peat production. By contrast, peatlands formerly drained for agriculture are rarely used for harvesting peat because of the problems involved in the traditional production method.

Peat is a domestic fuel of national importance to Finland and, considering its employment impact, it also has regional policy significance. Some 5 to 6% of Finland's overall energy demand is met by peat combustion. The energy yield of peat harvested in Finland is about 18 TWh per year, and its carbon content is about 1.35 million tonnes.

In international statistics (OECD/IEA/Eurostat), peat is equated with fossil fuels. In Finland, peat is classified as a slowly renewing biomass fuel, the time required for the peat layer to rebuild being very long. In the National Climate Strategy published in 2001 (VNS 1/2001 vp), it was noted that "*the basic principle underlying the comments [of the Finnish Government] on Community energy taxation is that peat is left for the national authorities to decide upon and thus outside the scope of the EC Directives on energy taxation.* [...] *In international statistical practice,* [...] *it is supported that peat would be separated from the fossil fuel category to form a category of its own.*" It was also noted: "*As far as the [United Nations Framework] Convention on Climate Change and other international cooperation are concerned, the following action will be taken:*

The need for supplementary studies will be mapped out and a research programme will be launched based on this mapping for a life cycle analysis of the energy use of peat.

If it is justified on the basis of the research findings, measures will be undertaken to influence the rules and definitions of the methodology used for calculating greenhouse gases by virtue of the international Convention on Climate Change. In this, the aim will be that the calculation methods subject to the Convention would take the greenhouse gas balance of peat into account during the entire life cycle and not just the emissions from combustion.

To be able to influence the Convention on Climate Change, clear criteria, besides new research data, will be required for the energy use of peat. The criteria shall state e.g. the definition of those peat lands on which the production of energy peat will be directed, as well as the requirements for subsequent use of the peat production areas."

Related to the preparation of the Climate Strategy, the Ministry of Trade and Industry commissioned in January 2001 a survey of the need for further research into the life cycle analysis. The purpose of the survey was "*to estimate what information will be needed to scientifically motivate, if possible, the introduction of calculation methods better taking into account the life cycle of peat in calculating emissions from the use of peat under the principles of the Kyoto Protocol.*" Another motivating factor was Finland's obligation to report on emissions from peat and peatlands under the United Nations Framework Convention on Climate Change (UNFCCC), the aim being to further specify these values.

In terms of climate impact, it would make sense to direct peat harvesting to areas where anthropogenic greenhouse gas (GHG) emissions are high, meaning that the cessation of these because of the area is taken over for fuel peat harvesting would compensate for some of the greenhouse impact of the burning of that peat. Similarly, the after-use of areas where peat harvesting is discontinued should be planned so that the life cycle greenhouse impact of the use of those areas would be as low as possible.

As a result of the information needs outlined above, a four-year research programme (2002–2005) was set up, jointly funded by the Ministry of Trade and Industry, the Ministry of Agriculture and Forestry and the Ministry of the Environment. Its principal purpose was to establish the levels of GHG emissions from the use of peat and peatlands in Finland. The research programme also drew up models for the GHG balances of peatlands in various types of land use and quantified the underlying ecosystem processes. The purpose of the component research projects was to establish the GHG balances of pristine peatlands and peatlands in various types of land use and using them as a basis for undertaking a life cycle analysis of various types of production chains in the harvesting and use of fuel peat. The purpose of a life cycle analysis is to assess the overall climate impact of peat, taking into account all the significant emissions and sinks involved in the product. As an approach this differs from the normal GHG inventory, which aims to present actual GHG emissions and sinks as accurately as possible for the report year only.

This publication contains a brief description of the aims, methods and principal findings of the studies carried out in the research programme, together with a synthesis of the new findings and earlier data. More detailed descriptions of each study are available in the respective research articles on them.

2. Implementig the research programme

The research programme consisted of nine research projects under a coordinating project. Some of these were 'method projects', while others concerned a specific sector of land use. The practical work involved was carried out in cooperation with three universities and four research institutions: the Universities of Helsinki, Joensuu and Kuopio, the Finnish Forest Research Institute (Metla), the Finnish Meteorological Institute, the Geological Survey of Finland and VTT Technical Research Centre of Finland.

Steering group:

The research programme projects, their relationships and their principal researchers are shown in Figure 1. All researchers who took part in the research projects are listed in the Appendix.

Funding:

The funding and human resource input, analysed by principal funding provider, for the period 2002–2005 were as follows:

Funding provider	**Person-years**	**Funding (EUR)**
Ministry of Trade and Industry	10.2	562,611
Ministry of Agriculture and Forestry	9.8	447,899
Ministry of the Environment	2.9	119,819
Other *)	35.9	1,909,081
Total	58.8	3,039,410

*) Ministries of Labour and Justice, Metla, VTT, Finnish Meteorological Institute, Universities of Helsinki and Joensuu, Vapo Oy, and funding from the Academy of Finland.

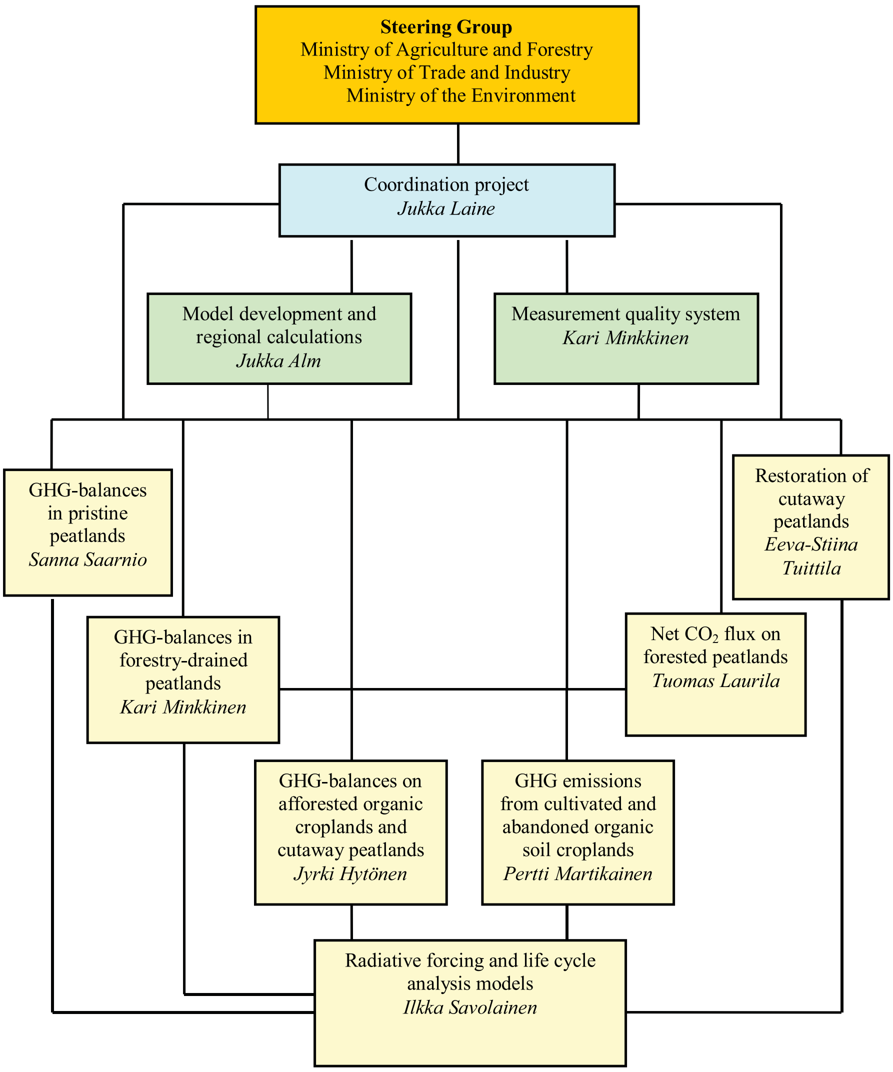

Figure 1. Structure of the research programme and principal researchers. The green boxes represent 'method projects', while the yellow boxes represent projects involving greenhouse gas balances in specific sectors of land use.

3. Use of peat and peatland as a source of greenhouse gas emissions

3.1. Pristine peatlands as greenhouse gas sinks and sources

Sanna Saarnio, Micaela Morero, Markku Mäkilä, Jukka Alm

3.1.1. Background

A pristine peatland (mire) is an ecosystem where the decomposition of dead vegetation is slower in the long term than the formation of litter from the primary production of plants. This results in part of the plant residue stratifying into peat. In primary production, carbon dioxide (CO_2) from the atmosphere is absorbed by vegetation and returned into the atmosphere through respiration of heterotrophic organisms. In a wet environment, the lack of oxygen slows down decomposition, and dead vegetation may be stored in the ecosystem for very long periods of time. However, some of the absorbed carbon returns into the atmosphere in the form of methane (CH_4), the end product of anaerobic decomposition chains. Also, carbon enters the peatland ecosystem with rainwater and groundwater and is carried out with runoff water. However, CH_4 and dissolved carbon only account for a few per cent of the annual carbon balance compared with CO_2 absorption and respiration.

Peatlands thus have dual significance for the greenhouse effect. It is estimated that the peatlands of the boreal and sub-arctic zones have absorbed more than one fifth of all the carbon in the soil. While pristine peatlands have decreased the greenhouse impact by absorbing carbon from the atmosphere, the release of CH_4 from anaerobic decomposition chains into the atmosphere has helped maintain the natural greenhouse effect. However, human activity is increasing the level of many greenhouse gases in the atmosphere, which will probably lead to an acceleration of the greenhouse impact and global climate change. Warming climate and redistribution of rain patterns geographically and temporally may change current habitats and communities and also the functioning of societies. Also, CO_2 and CH_4 fluxes between peatlands and the atmosphere change as circumstances change.

3.1.2. Aim of the study

Carbon stored in peatlands is one of Finland's most important sources of domestic fuel. Taking a peatland into energy production discontinues the natural functioning of its ecosystem. The removal of living vegetation prevents CO_2 absorption, and drying oxidizes the peat layers, thus increasing CO_2 release, although CH_4 release is minimized. The peat is harvested and burned, and as a result the carbon stored in it over thousands of years is released back into the atmosphere in a matter of decades. After peat harvesting, the cutaway peatland is afforested, re-wetted, left to regenerate naturally or planted, for example, with reed canary grass. As the area re-acquires vegetation, it gradually begins to absorb CO_2 again. Depending on the form of after-use and the climate conditions, the new ecosystem evolving in the area may begin to function as a carbon sink. This study focused on the annual greenhouse gas exchange and carbon balance of different types of pristine peatlands under current conditions and on the carbon accumulation of the past centuries and decades. The ultimate aim was to draft average annual balances for CO_2 and CH_4 in pristine peatlands.

3.1.3. Research methods and principal results

Field measurements

Literature was reviewed to find information on the annual CO_2 and CH_4 balances of peatlands in the coniferous forest belt, in Finland and abroad. The data collated cover the entire boreal belt of North America, Russia and Scandinavia, reflecting how peatlands in general perform in this climate zone.

In addition to the literature review, carbon gas exchange was measured on two different types of peatland in the municipality of Anjalankoski in the region of Kymenlaakso (in southern Finland). The two study sites were a sparsely forested ombrotrophic raised bog (Haukkasuo, 60°49'N 26°57'E) and the minerotrophic fen lagg of another raised bog (Hangassuo, 60°47'N 26°54'E), chosen so as to complement the range of sites in much-studied areas and other component projects. In life cycle analyses, peatlands are divided into two main groups: nutrient-poor peatlands sustained mainly by rainwater (ombrotrophic peatlands) and peatlands which besides rainwater also receive nutrients from groundwater and runoff water (minerotrophic peatlands). This division was employed in the present study too. In practice, both these

 

Figure 2. Tuulia Tanttu measuring net carbon dioxide flux at Hangassuo in summer 2003; Micaela Morero taking gas samples for measuring carbon dioxide and methane exchange in winter 2003.

groups contain a wide range of peatland types differing greatly in terms of wetness and vegetation.

Primary production and decomposition were monitored at different times of year, using the generally employed closed chamber method (Figure 2). Environmental factors known to be important were also measured at the study sites: temperature, photosynthetically active radiation, water table level, and the quantity and quality of vegetation. Using non-linear regression models representing the relationship between environmental factors and gas exchange and environmental time series, the carbon gas fluxes for both sites over the study period, 2002 to 2004, were reconstructed. Carbon accumulation at the same sites over the past decades and centuries was examined by taking peat core samples and analysing their dry matter density, carbon content and age (^{13}C and ^{14}C dating).

Carbon gas fluxes in peatlands are dynamic

Primary production and decomposition vary according to light, temperature and humidity, daily and annually. The differences in the quantity and quality of vegetation between peatland types and even between different types of surface structure in the same peatland have a substantial effect on CO_2 and CH_4 fluxes. Depending on what the weather is like, the annual CO_2 balance may represent a net efflux (emission)(–) or net influx (accumulation)(+). The CO_2 balance of pristine ombrotrophic peatlands in the boreal belt has been found to vary between –85 and +67 g C m^{-2} a^{-1}. The corresponding estimate for minerotrophic peatlands is between –101 and +98 g C m^{-2} a^{-1}. Thus, even in pristine peatlands in some years decomposition exceeds carbon absorption, and the carbon storage sink decreases. A negative annual balance is created when the water table level sinks lower than usual during the growing season. A dry spell of only a few weeks is enough to speed up aerobic decomposition in the exposed layer so that the annual balance turns negative. In the long term, however, the wet years have outnumbered the dry ones, as witnessed by the accumulation of peat.

In wet and therefore anoxic peat layers, anaerobic decomposition produces CH_4 as its end product. The annual CH_4 emission is the greatest in wet peatlands with large numbers of vascular plants. The differences in CH_4 emissions may be huge between different types of peatland and even between different types of microsite surface in the same peatland. Measurements show that the level of CH_4 emissions is less than 1 to 16 g C m^{-2} a^{-1} for ombrotrophic peatlands and less than 1 to 42 g C m^{-2} a^{-1} for minerotrophic peatlands. In a wet and warm year, the local CH_4 emission level may be double that of a cool and dry year. Because studies on CH_4 have been conducted on many different types of peatland in years with different weather, they probably reflect well the actual variations in the level of CH_4 emissions in boreal peatlands.

From measurements to models and predictions

Regression models were built to illustrate the relationship between the measured carbon gas fluxes and environmental factors, enabling the study of the annual variation in the CO_2 and CH_4 balance at the same sites over a period longer than the measurement period of three years. Typical weather for the region over a 30-year period was simulated using the *Finnfor* weather simulator. The weather variables (temperature, rainfall) were used to calculate ambient temperature and moisture for the study sites over the period simulated. For annual vegetation development, models were built using field observations. These time series were used as input data for the regression models, and the end result was an hour-by-hour carbon gas exchange pattern for both study sites over a period of 30 years.

The coverage of the regression models was good. Development needs were found in the accurate modelling of temperature and water table level at the study sites. However, the models do yield findings for this one peatland similar to those concluded on the basis of field observations at several sites for previous individual years. As long as climate change does not lead to vegetation change, photosynthesis rate fluctuations from one year to the next will remain slighter than decomposition rate fluctuations (Figure 3).

Dryness and heat favour aerobic decomposition, which may lead to the peatland emitting more CO_2 than it absorbs. Although increased oxidization of the peat reduces the amount of carbon emitted into the atmosphere with CH_4, the total carbon sink of the peatland is reduced in such years. On the basis of carbon gas balances calculated for the years of study, both peatlands loosed carbon in 2002 and in the exceptionally dry year of 2003 (Figure 4).

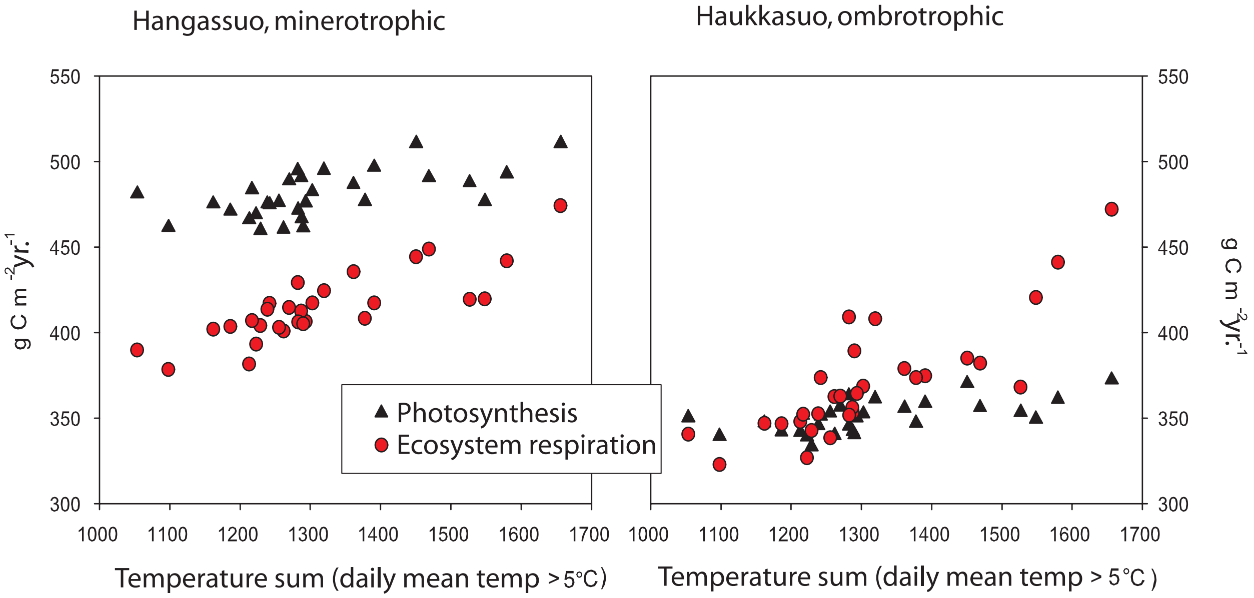

Figure 3. The simulated CO_2 exchange at Hangassuo and Haukkasuo was the higher the greater the annual temperature sum was. The temperature sum is the accumulation of the daily mean air temperature exceeding 5 °C. The variation in weather conditions in the simulated years correlated with the actual variation in weather conditions in Anjalankoski between 1961 and 1990.

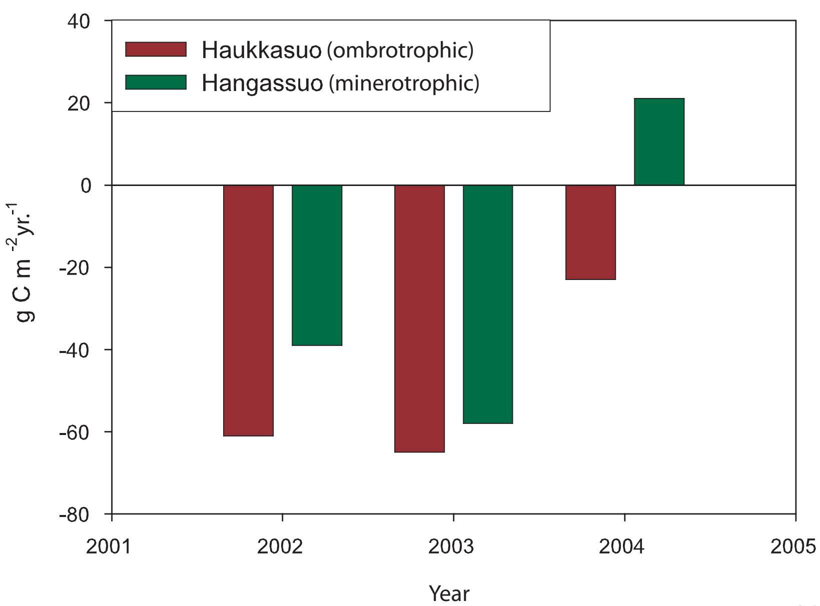

Figure 4. Carbon gas balances at Haukkasuo and Hangassuo study sites in Anjalankoski in the study years 2002 to 2004. The Haukkasuo site was an ombrotrophic raised bog, while the Hangassuo site was a minerotrophic fen lagg.

In the wettest year 2004, the minerotrophic fen lagg at the Hangassuo site would seem to have acted as a carbon sink, but the ombrotrophic Haukkasuo site would still seem to have released slightly more carbon than it absorbed. Because the water table level has been lower than average in three of the six years that have so far elapsed of this decade, there is reason to believe that the peat stock at the study sites has not increased at all in the present millennium (Figure 5).

Recent carbon accumulation

Samples taken from the top peat layers were analysed for age, dry matter density and carbon content. This showed the carbon accumulation rate of slightly decomposed litter and the carbon it contains. The fen lagg seemed to acquire much more litter than the raised bog, but decomposition reduced this amount so that over time the remaining amount is roughly the same as in the raised bog (Figure 6). On the top of the peatland, most of the vegetation a few years old is still not decomposed, but at a depth of only 20–40 cm only a fraction remains of vegetation decades or centuries old. It is only deeper, in the permanently anoxic layer under the water table level, that the peat and the carbon it contains accurately reflect the carbon accumulation of the peatland. However, decomposition continues in anaerobic conditions, too, so the carbon accumulation rate is in any case relative, and the accumulation rate for carbon ab-

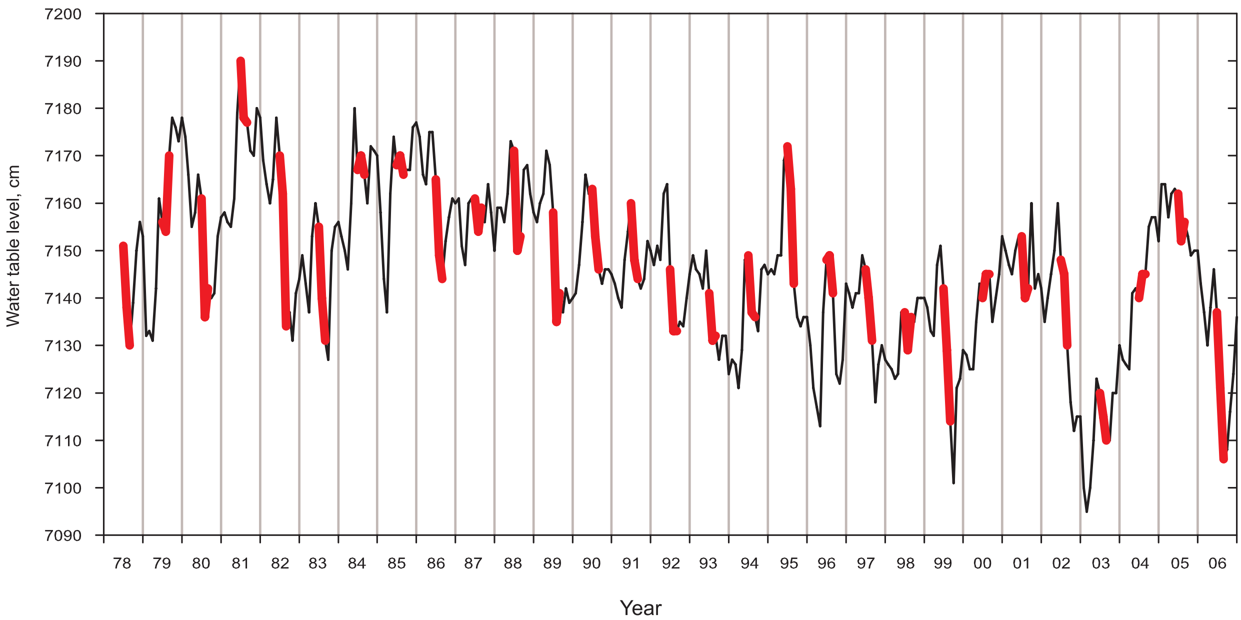

Figure 5. Water table level of peat compared with sea level at the official Finnish Environment Institute measuring point nearest to the study sites (Valkeala 60°55'N, 27°02'E). The values for the period most critical for carbon absorption (June–August) are given in the time series in red.

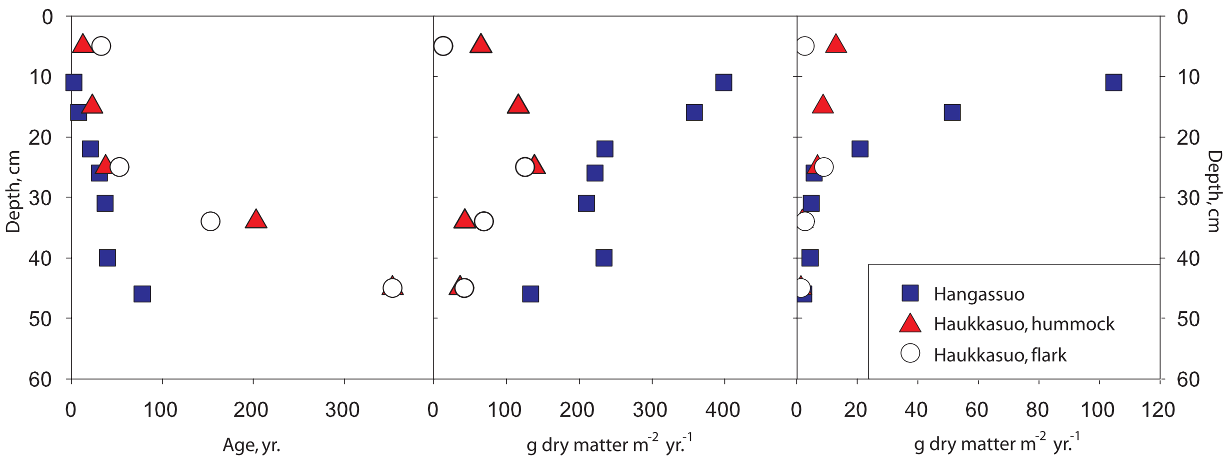

Figure 6. Peat age, virtual peat accumulation and remaining dry matter relative to the age of the sample, at various depths at the Hangassuo and Haukkasuo study sites. Hummocks are dry surfaces in a raised bog and hollows are wet surfaces. About 40–50% of the dry matter is carbon.

sorbed at a particular time decreases over time as the decomposition of the dead vegetation progresses. For example, the current litter accumulation rate in the top peat layer at Hangassuo is almost 200 g C m^{-2} a^{-1}, whereas the long-term average carbon accumulation, based on the thickness of the entire peat layer and the ages of its various strata, is 22 g m^{-2} a^{-1} at both Hangassuo and Haukkasuo, according to the Geological Survey of Finland (GTK). In Finland as a whole, the average carbon accumulation rate since the latest Ice Age has been 17 g C m^{-2} a^{-1} in minerotrophic peatlands and 21 g C m^{-2} a^{-1} in ombrotrophic peatlands. Although the long-term carbon accumulation at the study sites of the present study concur with these figures, carbon accumulation has varied greatly over comparable periods of time, depending on the evolution stage of the peatlands, the climate and local circumstances. Whether the carbon stock in peatlands will increase or decrease and what the long-term accumulation rate will be in the future for the peat layer as a whole depends on the weather or, more specifically, on how common dry spells during the growing season will be in the future.

Outlook

The functioning of peatlands depends on local circumstances. Changes in the atmosphere and in land use will thus continue to have a direct impact on the functioning of peatland ecosystems. For example, anthropogenic increase of CO_2 in the atmosphere will increase the amount of carbon both absorbed and released by peatland ecosystems. Thus, depending on the weather, peatlands will be even greater carbon sinks or an even greater source of net emission in the future, assuming that CO2 level is the only parameter to change.

However, it is estimated that Finland will have a warmer climate in the future, particularly in the autumn and winter, and that a higher rainfall is to be expected than at present. Dry spells during the growing season, which have become commonplace in recent years, may lead to an annual net emission of carbon from peatlands. Warm autumns will increase decomposition but, on the other hand, the snow melting earlier in spring will bring forward the beginning of carbon absorption at least by plants which stay green in the winter.

Longer-term changes in the weather and thus in the circumstances of ecosystems may cause major changes in flora and fauna, too. Other factors such as increased UV radiation, increased ozone levels in the lower atmosphere or chemicalization of our environment make it even more difficult to predict how primary production, decomposition and peat accumulation will evolve in peatlands.

3.1.4. Conclusions

- Only a fraction of the vegetation which accumulates on the top of pristine undrained peatlands ends up being stored as peat. The occurrence of dry spells during the growing season, which recently has become more frequent, has slowed down the accumulation rate of peat in peatlands in Finland. Dry spells are thus a highly significant factor for peat as a carbon sink.

- The study shows that the carbon dioxide and methane fluxes in pristine peatlands vary widely depending on the weather and the type of vegetation. This natural variation causes great diversity in average annual balances. This could be reduced by categorizing peatlands into more groups than just the main two, ombrotrophic and minerotrophic, and by conducting further research.

- Current knowledge does not provide a sufficient overall view of the fluctuation over time of the carbon dioxide balance in peatlands of different types. The information on methane emissions is more reliable.

- On the basis of the problems which emerged in the modelling of carbon balances, the following points should be addressed: 1) developing models based on various processes in the carbon cycle rather than blanket regression models; 2) taking into account the effect of water table variation in the surrounding areas on peatland water balance models; 3) developing modelling of the annual variation in vegetation to account for the weather; and 4) securing that diverse field measurements are obtained over the long term so that reliable models for predicting carbon gas exchange and thereby carbon accumulation under changing circumstances can be developed.

3.2. Greenhouse gas emissions from forestry-drained peatlands and contributing environmental factors

Kari Minkkinen, Jukka Laine, Timo Penttilä

3.2.1. Background

Covering some 5 million hectares, forestry drainage is a potentially significant contributor to greenhouse gas emissions in Finland. The drainage was mostly carried out between the 1960s and 1980s and today contributes an extra growth amounting to more than 13 million cubic metres of wood per year. Much of the forests growing in these areas is due for thinning. But how do drainage and forestry affect greenhouse gas emissions on forestry-drained peatland?

Drainage lowers the water table level of a peatland, oxygenates the top strata of the peat and thereby enables the growing of trees on the peatland. The increased oxygen level in the top stratum of the peat accelerates decomposition, leading to increased emissions of carbon dioxide (CO_2) and, in nutrient-rich peatlands, possibly also increased emissions of nitrous oxide (N_2O). On the other hand, this decreases and often completely prevents emissions of methane (CH_4), a product of anaerobic decomposition as the top strata of the peat become oxidized and the deep-rooted peatland vegetation disappears.

A pristine sedge fen (left) and the same fen 40 years after drainage. The drainage has considerably increased tree growth while also radically changing the surface vegetation species. Peatland vegetation has been replaced by species typical of a heath forest. (Photo: Sakari Sarkkola).

After drainage, the carbon bound in the biomass in the area (mainly the trees) increases strongly. Nevertheless, as a whole litter production of the peatland (i.e. the carbon flow at ground level) will not necessarily increase, since the biomass remains bound in the above-ground portions of the trees growing in the area until they are felled/cut down. By contrast, the changes in underground production (root growth and death) can be very substantial, but this process is poorly known as yet. However, the litter becomes woodier and decomposes more slowly compared with the situation before drainage. The temperature and pH of the peat decrease as the trees grow, and both factors slow down the decomposition of organic matter. Cuttings in forestry-drained areas typically raise the water table level, whereas the soil preparation involved in restoration, e.g. mounding, leads to the peat mounds becoming oxidized, which may reaccelerate decomposition. On the other hand, excess dryness may limit decomposition in the summer months.

Thus, whether a peatland turns into a carbon source after drainage or whether it continues to accumulate organic matter depends on changes in the relationship between decomposition and production. Earlier measurements indicate that both trends are possible and that the outcome is influenced by the geographical location of the drained peatland and its ecohydrological status before drainage.

3.2.2. Research methods and aims

There are two principal methods for measuring greenhouse gas emissions: 1) the closed chamber method, which enables measurement of gas exchange of the soil and surface vegetation, and 2) the micrometeorological covariance method (eddy covariance method), which enables measurement of the gas exchange (usually CO_2) of the entire ecosystem above the treetops (see Laurila et al. 2008 p. 38 in this report). Soil gas fluxes in forestry-drained peatland has previously been measured at a few locations in central and eastern Finland, but the CO_2 exchange of an entire peatland has not been measured earlier. The tower method gives the CO_2 balance for the entire ecosystem under measurement, but dividing this balance into components (trees, surface vegetation, soil) is not possible without further measurements. The closed chamber methods can be used to measure the contributions of soil components (peat, litter, roots) and surface vegetation to gas exchange, leaving the contribution of the trees to be modelled through growth and litterfall models.

In this research project, the closed chamber method was used to study gas fluxes of the soil. Specifically, 1) the effect of fellings on greenhouse gas emissions from the soil was studied through felling studies in southern and northern Finland; 2) greenhouse gas fluxes were measured in various drained areas under different climate conditions; and 3) gas fluxes were statistically modelled using statistically measured environment factors. Using statistical models and weather simulations, 4) the amount of greenhouse gases released from peat in various drained areas were estimated; and 5) the overall amount of greenhouse gases released from drained peatland in Finland annually was estimated. Carbon fluxes into the soil were also estimated by modelling tree yield and litterfall using the *Motti* model (Hynynen et al. 2005) and litter decomposition in the topsoil using the *Yasso* model (Liski et al. 2005). The overall carbon balance of forestry-drained peatland was estimated by combining the results of the production and decomposition models (Figure 7).

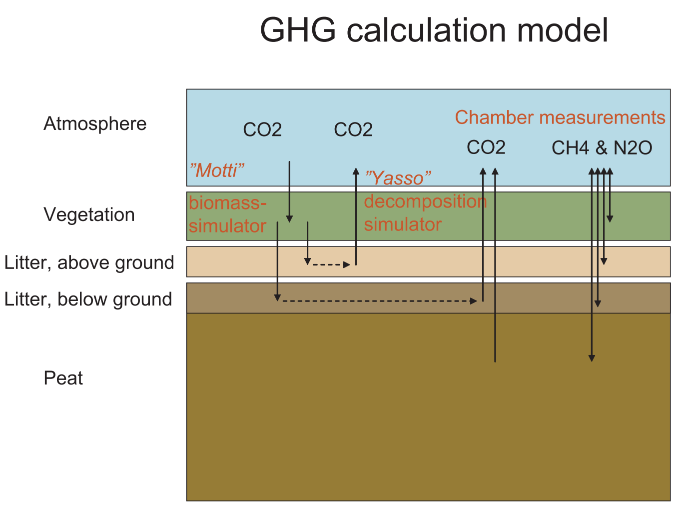

Figure 7. Conceptual model used for calculating greenhouse gas balances.

3.2.3. Results

Carbon dioxide (CO_2)

Emissions of carbon dioxide from forestry-drained peatland were measured on sample plots where ground vegetation and litter had been removed, and roots had been cut one year before measurements were begun. The CO_2 emissions measured were therefore due only to the decomposition of organic matter in the peat (including the cut roots).

Temperature is the most important factor affecting the decomposition of organic matter and hence the volume of CO_2 released from peatland in forestry-drained peatland. About 90% of the variation in CO_2 emissions at the same location over time can be explained by soil temperature. However, there is great spatial variation. Emissions are affected not only by temperature but also by the composition of the organic matter in the peat and its microbe populations, but so far it has been difficult to model these. Unlike in pristine peatlands, in forestry-drained peatland the water table level is in most cases in so deep that its variations usually have only a minor effect on CO_2 emissions, since most of the CO_2 released through the decomposition of organic matter comes from new litter and the top strata of the peat.

There were significant differences in CO_2 emissions between new test sites on forestry-drained peatland studied. There was a clear increasing trend in emissions from nutrient-poor peatland to nutrient-rich peatland, which was expected. What was unexpected was the result of comparing southern and northern sites: emissions in comparable peatland areas were highest in the north, even though the temperatures were lower than in the south. As CO_2 emissions correlate to a great degree with temperature, the effect of different years was tested by simulating emissions in the measurement areas using weather data for a period of 30 years. The annual carbon emissions from organic matter decomposition for the southern *Vaccinium myrtillus* peatland type were about 350 g m^{-2}, while the figure in the north was more than 470 g m^{-2} (Figure 8). A significant difference was caused by winter emissions being substantially smaller in the south than in the north, since in the north the thick snow cover insulates the soil, whereby decomposition can continue in the topsoil almost through the winter. Nutrient status of the soil or water table levels of the peat provided no clear indicator for these differences. However, the study

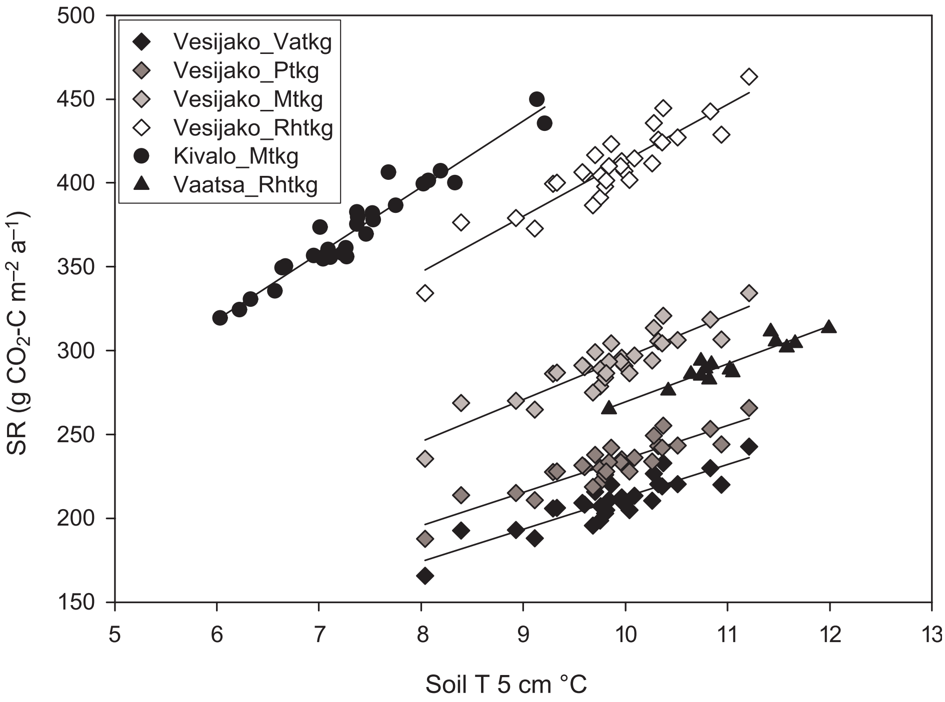

Figure 8. Simulated CO_2 emissions from decomposition in peatland at various measurement sites, relative to soil temperature. In the simulation, the emission regression models were run with input data consisting of hour-per-hour weather data from a period of 30 years. In the figure, each dot represents the total emissions for one year.

material is so limited that no conclusions can be drawn regarding whether these findings can be generalized to apply to all forestry-drained peatland or whether these are just properties of the specific sites studied. The results are being tested and their general validity examined in a new project financed by the Ministry of Agriculture and Forestry (Carbon balance of forested peatlands – predictions and monitoring in changing conditions), where CO_2 measurements are being carried out at some 70 sites all around Finland.

The soil respiration measurements only account for CO_2 released from the soil. The soil CO_2 balance of forestry-drained peatlands was estimated by combining the soil respiration measurement results with the modelled carbon binding figures. The model calculations show that in most cases the amount of CO_2 released from the soil exceeded the amount of CO_2 bound, leading to a negative CO_2 balance. The soil of such forestry-drained peatlands was thus shown to be a source of carbon emissions into the atmosphere.

Based on earlier studies, we have suggested that the soil carbon balance of forestry-drained peatland is, on average, positive (i.e. that forestry-drained peatland is a carbon sink). Positive balances were observed on nutrient-poor peatland and negative balances on nutrient-rich peatland. The soil respiration results obtained now show the same trend: the modelled carbon absorption completely or almost completely compensates for the measured decomposition in the more nutrient-poor site types, but in nutrient-rich site types and in northern Finland, in particular, the soil carbon balance was decisively negative (Figure 9). However, when the carbon absorbed by the trees over the long term (1st cycle) was included in the calculation (including an estimate of the carbon removed in connection with cutting), the carbon balance for the ecosystem as a whole usually turned out to be positive (Figure 9).

In this research programme, the CO_2 balance was measured directly for the first time using the Eddy covariance method, at two forested locations in southern Finland – afforested organic cropland and a nutrient-poor forestry-drained peatland site. The former turned out to be a source of carbon and the latter a carbon sink. When the carbon absorbed by the trees during the measurement interval was subtracted from the total net exchange of carbon, the net emission from the soil (and surface vegetation) of the afforested organic soil cropland was c. 250 g C m^{-2} a^{-1}, while the forestry-drained peatland showed a net accumulation of more than 100 g C m^{-2} a^{-1}. These results support earlier findings that there is great variation in carbon dynamics between different types of drained peatland, and that even drained peatlands can function as significant carbon sinks.

Naturally, there is much scope for error in both the modelling and the measurements. The production models are based on limited information regarding, for example, underground production, and the decomposition models have not yet been calibrated for peatland. There may be systematic errors in the measurements due to site processing (root

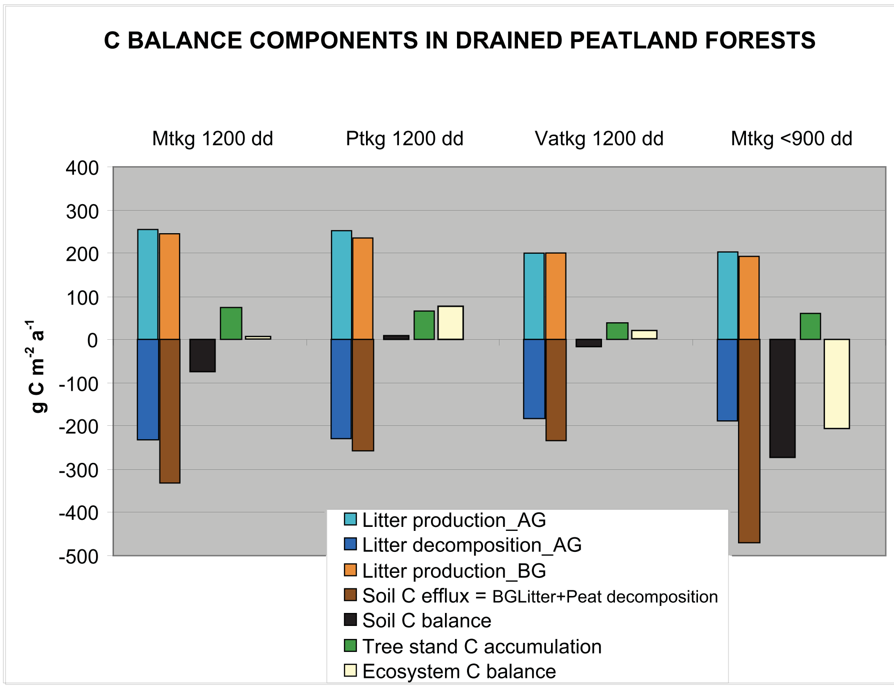

Figure 9. Sample calculation of carbon fluxes in drained peatlands of different types (Vatkg–Mtkg) in southern Finland (1200 dd) and northern Finland (<900 dd). Negative figures refer to net carbon emission and positive figures to net carbon accumulation. AG = above ground, BG = below ground.

cutting and vegetation clearing). Further research will be undertaken to estimate the effects of these sources of error.

Finland's first greenhouse gas inventory report drew on the findings of the modelling method, which showed that the overall carbon balance of forestry-drained peatland in Finland was negative. However, because of the great variation observed and the partly conflicting results obtained through different research methods, we cannot yet assess the reliability of this modelling calculation. Estimates will improve as research data with better regional coverage will be obtained in the near future.

Methane (CH_4)

The situation with regard to methane is considerably simpler than that of carbon dioxide. Emissions of CH_4 decrease as time passes from the drainage, with the progression of drying and flora succession. The rate of drying succession depends on the changes that occur in the site's ecohydrology: in peatland types which are originally nutrient-rich and wet, the vegetation changes quickly, while in nutrient-poor peatland types the process is slower. The rate of change also correlates closely with the growth of the trees, and the CH_4 emissions correlate negatively with tree stand volume – as tree stand volume increases, the CH_4 emissions decrease. Indeed, it is quite possible to estimate CH_4 emissions on the basis of the tree stand volume in the area. Data gathered from Finnish peatlands suggests that, on average, CH_4 emissions cease when the tree stand volume exceeds 140 m^3 per hectare (Figure 10). This never happens on nutrient-poor forestry-drained peatland, but the more nutrient-rich peatlands become CH_4 sinks 20 to 30 years after drainage. Because all drained peatlands are still relatively young, and many of them are nutrient-poor, Finland's forestry-drained peatland is still a small source of CH_4 (0.048 Tg per year), albeit this figure has decreased considerably compared with the natural state.

Nitrous oxide (N_2O)

Generation of nitrous oxide is possible under conditions where nitrification and denitrification processes are active. In pristine peatlands, nitrification is prevented because of lack of oxygen, and in forestry-drained peatland the low pH inhibits the process. However, in nutrient-rich peatlands or fertilized drained peatland, N_2O can be generated, and substantial isolated emissions have been observed, for instance, in connection with the ground freezing. These emissions cannot yet be modelled at the process level, but there is a strong statistical correlation between the carbon-nitrogen ratio of the soil (CN) and its annual emissions: if there is a lot of nitrogen in relation to carbon (a low CN ratio), N_2O emissions increase. The dependency is a non-linear one, and a significant change occurs when the CN ratio falls from 40 to 20 (Figure 11). In drained spruce peatlands, CN ratios are considerably lower than in pine peatlands, which can also be seen in their bigger than

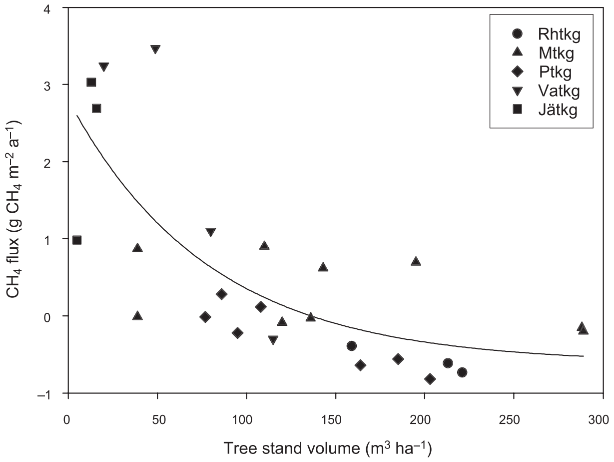

Figure 10. CH_4 emissions from forestry-drained peatland as a function of tree stand volume.

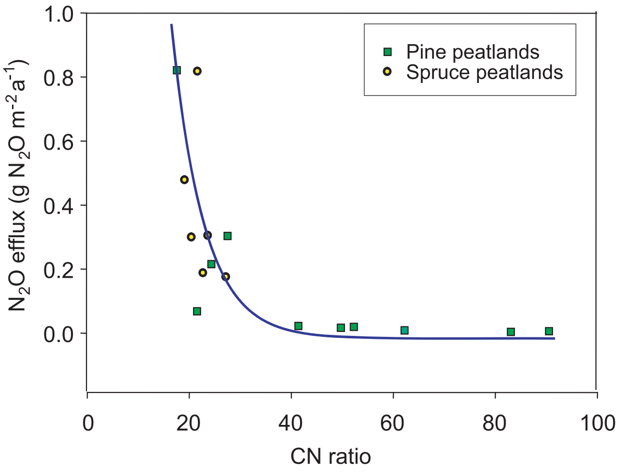

Figure 11. N_2O emissions from forestry-drained peatland as a function of the CN ratio.

average emission levels. We used the regression model and the CN ratio distributions of forestry-drained peatland together with peatland-type-specific CN ratios to predict N_2O emissions from Finland's forestry-drained peatland. The current emission prediction is, depending on the approach, between 0.010 and 0.015 Tg N_2O a^{-1}.

Impact of forest fellings on emissions

Felling of tree stand raises the water table level and the soil temperature slightly. Overall, CO_2 emissions from the soil decreased by 35 to 45%, corresponding to the volume of root respiration, but the volume of CO_2 released by the decomposition of old peat did not change. Felling thus had little impact on the soil carbon balance. The rise of the water table level in the felling area caused a slight decrease in the absorption rate of CH_4. N_2O emissions rose at the locations of felling residue piles. Obviously, felling residue releases nitrogen faster than the sparse local vegetation can use it, which leads to nitrification and the release of N_2O, an intermediate product in this process. On the whole, however, cutting has a minor impact on soil GHG balance.

3.2.4. Conclusions

- The results of the research project showed that the carbon dioxide balances of forestry-drained peatland vary greatly; an area may be a carbon source or a carbon sink, depending on the site and the climatic conditions. Carbon balances can be estimated using the existing models, but it is not yet possible to assess the reliability of the average values obtained due to the multitude of factors affecting emission dynamics.

- The results show that drying substantially reduces methane emissions if the drying succession is sufficient to cause a clear change in the flora and tree growth. Because in Finland many peatlands have been drained that are too nutrient-poor for profitable wood production, such peatlands continue to release methane into the atmosphere.

- According to new calculations made during the project, forestry drainage increases nitrous oxide emissions in nutrient-rich locations more than previously estimated. Drained spruce peatlands, in particular, are significant sources of nitrous oxide.

3.3. Greenhouse gas emissions from cultivated and abandoned organic croplands

Marja Maljanen, Jyrki Hytönen, Päivi Mäkiranta, Jukka Alm, Kari Minkkinen, Jukka Laine, Pertti Martikainen

3.3.1. Background and aim

About 0.7 million ha of Finland's peatlands have been drained for agriculture. About half of these areas have been abandoned or afforested, but about 300,000 ha are still in agricultural use (Myllys & Sinkkonen 2004). In agriculture, a lowering of the water table level, repeated tillage, fertilization, liming and mineral soil addition change the properties of peatland. These also enhance the formation and fluxes of greenhouse gases (GHGs). Drained organic cropland is always a net emitter of carbon dioxide (CO_2) and (N_2O), but it may be a weak methane (CH_4) sink.

The global warming potential of nitrous oxide is 296 times and methane 23 times than that of carbon oxide, in a 100-year time horizon (IPCC 2001). Agricultural soils are responsible for most of the global N_2O emissions from soils. A pristine peatland emits hardly any N_2O at all, but drainage increases emissions of N_2O from organic soils and organic croplands are particularly important as regards the atmospheric N_2O load. As much as 25% (4 Tg annually) of the N_2O emissions in Finland may originate from organic croplands (Kasimir-Klemedtsson et al. 1997), although these soils represent only 13.6% of the total agricultural land in the country (Myllys & Sinkkonen 2004). N_2O is produced in soil microbial activities, with nitrification and denitrification as the key processes, with contributions from environmental factors such as temperature, soil moisture, soil pH and vegetation. Cultivation practices such as tillage, fertilization, irrigation and compaction of soil by machinery can also affect the N_2O production. Winter emissions should be given particular attention in boreal areas, as they can account for more than half of the annual N_2O emissions.

Methane from agriculture originates mainly in the digestion of ruminants, manure management and from waterlogged soils such as rice paddies. Well-drained organic croplands are generally sinks for CH_4 because CH_4 is oxidized by methanotrophic bacteria. The water table level, temperature, nitrogen fertilization, liming, tillage and other similar measures can affect CH_4 fluxes.

After the cultivation practices have ceased, gradual secondary vegetation succession starts. Grasses and herbs dominate in field vegetation for 15 years, and open field ditches are the first habitat for the pioneer tree species (birch and willow). The gradual deterioration of the ditches leads to higher water table levels, which may increase CH_4 emissions. On the other hand, ending cultivation practices may reduce the decomposition rate of peat and thus also CO_2 and N_2O emissions. The annual GHG emissions from Finnish organic croplands in active use were measured at five sites. In this paper we summarize the results of these studies. We also report the annual and seasonal GHG emissions from five abandoned organic croplands and discuss how GHG emissions change after cultivation practices have ceased.

A summery barley field on organic cropland in southern Finland (Photo: Sakari Sarkkola).

Table 1. Test sites: Cultivated sites: 1. Jokioinen (Regina et al. 2004, Regina et al. 2004, Regina et al. 2006), 2. Liperi (Maljanen et al. 2001, 2003a, b), 3. Ilomantsi (Nykänen et al. 1995), 4. Rovaniemi (Regina et al. 2004, Regina et al. 2006), 5a. Kannus, (two subsites with different peat depths) (Maljanen et al. 2004); Abandoned soils: 5b. (5 sites).

Site	C/N	Bulk density (g cm^{-3})	pH (H_2O)	Peat depth (m)	Drainage (years ago)
1.	21	0.49–0.51	5.8	nd	100
2.	16	0.33	6.0	0.2	40
3.	19	nd	5.3	1.4	60
4.	18	0.24–0.29	5.6	nd	50
5a.	31–32	0.32–0.50	4.8	0.3–0.7	nd
5b.	16–19	0.33–0.47	4.3–5.9	0.2– >1.0	50–100

nd = not determined

3.3.2. Materials and methods

GHG fluxes on organic croplands

Annual N_2O and CH_4 emission measurements were carried out at five different sites between 1991 and 2002. N_2O and CH_4 fluxes were measured using a chamber method. CO_2 balances were measured at two sites using a chamber method and at two sites using the eddy covariance (EC) method. The measurements were made on soils under barley or grass. Sites with no vegetation (fallow) were also studied (Table 1).

GHG fluxes on abandoned organic croplands

N_2O and CH_4 fluxes were measured between 2002 and 2005 on five abandoned organic croplands in Kannus, western Finland (Table 1). There were altogether 30 gas sampling plots on these fields. These sites were drained and used for cultivation for decades before being abandoned (no fertilization or ploughing) 20 to 30 years ago.

CO_2 exchange between the soil-vegetation system and the atmosphere was measured using a chamber method between 2002 and 2004. The results given here are preliminary results for 2003. The net ecosystem CO_2 exchange (NEE) was measured with a transparent climate-controlled chamber (60 x 60 cm, height 30 cm) that was placed on an aluminium collar set in the ground throughout the measurement. The collar had a groove in the upper edge which was filled with water to ensure a gas-tight seal. A CO_2 analyser (EGM-4 Environmental Gas Monitor for CO_2, PP Systems, UK) monitored the change in the CO_2 concentration in the chamber during the chamber closure period of 180 seconds. Simultaneously, the light intensity (PAR) and air temperature (T_a) inside the chamber were recorded. The measurements were made in full light and then in reduced light under mosquito netting. After that, the gross respiration rate (R_{TOT}) of the plant-soil system was measured in the same way by covering the collar with an opaque cover.

NEE and R_{TOT} were calculated from the linear increase or decrease in the CO_2 concentration in the chamber. CO_2 uptake from the atmosphere into the soil is designated with a positive, and release of CO_2 from the soil into the atmosphere with a negative sign. NEE can be positive or negative, while R_{TOT} is always negative. An estimate of gross photosynthesis (P_G) was calculated using the formula: $NEE = P_G - R_{TOT}$ (1).

For calculation of the diurnal cycles of NEE, the values for P_G and R_{TOT} were needed for every hour. Statistical response functions were constructed separately for each site in order to predict P_G and R_{TOT} (e.g. Alm et al. 1997). The model included gross photosynthesis, photosynthetically active radiation, leaf area index, soil temperature at a depth of 5 cm, and water table level.

The diurnal cycles of P_G and R_{TOT} were then reconstructed using the above model and continuous data for the environment variables. The net CO_2 emission for the growing season was calculated from the hourly values of NEE. Outside the growing season, the net CO_2 flux was measured similarly to the N_2O and CH_4 fluxes (see next section).

N_2O and CH_4 flux measurements were made on abandoned organic croplands over three years. The results reported here are for 2003 and 2004. During the snow-free periods, fluxes of N_2O and CH_4 were measured every second week with the static chamber method. Gas concentrations were analysed within 24 hours of sampling with a gas chromatograph. During the winter snow cover, the gas fluxes were determined using the gas gradient technique, where gas samples for concentra-

Table 2. Annual measured GHG emissions on cultivated organic croplands in Finland. Negative figures indicate gas consumption on the ground. CO_2-C, CH_4-C and N_2O-N emissions are given as g m^{-2}.

Plant	Site	CO_2-C	CH_4-C	N_2O-N	Reference
Barley	1.	210	–0.01– –0.04	0.62–2.41	Lohila et al. 2004, Regina et al. 2004, 2006
Barley	2.	400	–0.37– –0.01	0.83–0.84	Maljanen et al. 2001, 2003a, 2003b
Barley	4.	nd	–0.02–0.38	0.73–1.88	Regina et al. 2004, Regina 2006
Barley	5a.	830	–0.13– –0.06	0.54–1.13	Maljanen et al. 2004
Grass	1.	80	–0.05– –0.01	0.50–0.99	Lohila et al. 2004, Regina et al. 2004, 2006
Grass	2.	750	–0.08	1.10	Maljanen et al. 2001, 2003a, 2003b
Grass	3.	nd	0.10–0.20	0.78–0.93	Nykänen et al. 1995
Grass	4.	nd	0.27–0.68	0.26–0.53	Regina et al. 2004, 2006
Grass	5a.	330–460	–0.07– –0.18	0.17–0.38	Maljanen et al. 2004
Fallow	1.	nd	–0.03– –0.01	1.34–3.70	Regina et al. 2004
Fallow	2.	880–1100	–0.26– –0.13	0.65–0.71	Maljanen et al. 2001, 2003a, 2003b
Fallow	4.	nd	0.04–3.00	0.38–0.50	Regina et al. 2004, 2006
Fallow	5a	690–790	–0.14– –0.01	0.40–3.70	Maljanen et al. 2004

nd = not determined

tion analyses were drawn from the snow pack using a stainless steel probe 3 mm in diameter. Gas fluxes from the soil through the snow pack into the atmosphere were calculated using Fick's law.

3.3.3. Results

At the annual level the cultivated organic croplands were all net sources of CO_2 (Table 2, Figure 12). The CO_2 losses measured with the chamber method from soil under grass varied from 79 to 750 g CO_2-C m^{-2} and CO_2 losses from under barley were from 210 to 830 g CO_2-C m^{-2}. The net CO_2 emissions from fallow soils (without vegetation) had a similar CO_2 net loss, from 690 to 1,100 g CO_2-C m^{-2}, as the barley fields.

The EC measurements showed lower CO_2 emissions than the chamber measurements. The CO_2 balance is very sensitive to climatic conditions, and therefore this difference can be partly explained by the variation in the environmental factors controlling CO_2 flux, because the EC and chamber measurements were conducted in different years, in different climatic conditions. However, the emissions are close to the net emissions, 400 to 550 g CO_2-C m^{-2}, estimated earlier for boreal organic croplands.

The abandoned organic croplands were either small net sinks of CO_2 (max. 90 g CO_2-C m^{-2}) or sources of CO_2 (max. net emission 900 g CO_2-C m^{-2}). All abandoned sites showed some net uptake of CO_2 during the growing season, but outside that period all abandoned croplands were sources of CO_2. The mean annual CO_2 emission, 324 g CO_2-C m^{-2}, is close to the net CO_2 emissions from cultivated croplands. It seems that

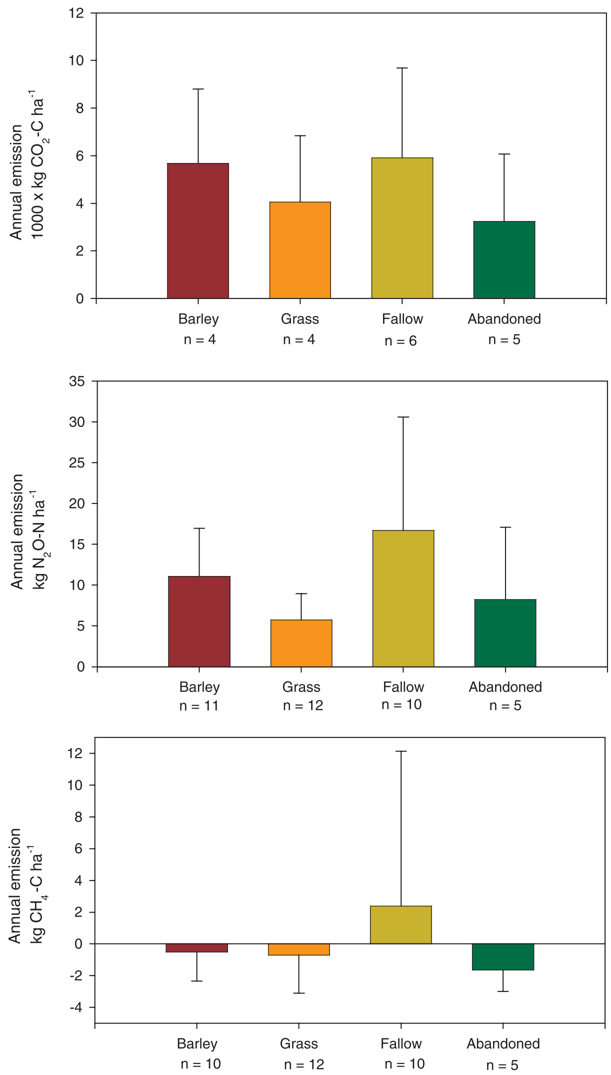

Figure 12. CO_2, N_2O and CH_4 flux averages for cultivated organic cropland, fallow soil with no vegetation and abandoned organic croplands. The error lines show the standard error of the average. n = number of annual emissions measurements.

abandoned organic croplands do not generally turn into CO_2 sinks quickly after the agricultural practices have ceased, although their net CO_2 emissions may be slightly reduced compared to cultivated croplands (Figure 12). As abandoned croplands slowly become afforested, the amount of carbon assimilated by the trees increases, decreasing emissions. Natural afforestation is rather slow, though (Hytönen 1999). Fallow soils, without vegetation, showed an almost similar CO_2 net loss as the barley fields.

Cultivated organic croplands were either small sinks or sources of CH_4 (Figure 12), depending on the water table level at the site. The fallow soils without vegetation had a lower CH_4 uptake than the cultivated soils, or the corresponding emission was greater (Figure 12). Although CH_4 fluxes seemed to depend on the weather at all the study sites, there was no correlation between the mean annual CH_4 flux and the mean water table level, pH, the soil C or N level or the CN ratio of soil. Annually, all the abandoned cropland soils were net sinks for atmospheric CH_4, though some periods of low CH_4 emissions were measured during the summer. Despite the deterioration of the ditch network after 20–30 years of abandonment, the water table level remained reasonably deep. The mean soil CH_4 uptake rate was even higher at the abandoned sites than at the cultivated sites. In other words, the ability of abandoned organic croplands to withdraw CH_4 from the atmosphere may increase gradually over time (Figure 12).

The mean N_2O emissions from croplands under barley were higher than those from croplands under grass (Figure 12), but N_2O emissions from bare soils were generally higher still. This may be related to higher nitrogen availability for denitrification in the absence of plants. Surprisingly, the N_2O emissions from the abandoned cropland soils were similar to or even higher than those from the cultivated croplands (Figure 12). The time since the end of cultivation practices did not correlate with the annual N_2O emission rates from the abandoned croplands. There is thus no evidence that the ending of cultivation activities would reduce N_2O emissions from organic croplands.

There was high variation in the seasonal and annual N_2O emissions, and only a part of this could be explained by weather conditions, e.g. temperature and precipitation. Generally, the annual N_2O emissions from the croplands and abandoned croplands did not correlate with the mean water table level, even though there was some correlation during the growing season. There was, however, a weak correlation between the carbon-nitrogen (CN) ratio of both cultivated and abandoned croplands and annual N_2O emissions. Klemedtsson et al. (2005) have recently reported that the CN ratio of afforested organic soils may predict annual N_2O emissions. However, in croplands other factors, e.g. fertilization and tillage, may overcome the CN dependence, which reflects the availability of mineral nitrogen for microbial processes important in N_2O emissions. The winter emissions (from October to May) of N_2O accounted for a significant portion of the annual N_2O emissions: 25% for grass, 50% for abandoned cropland and 60% for barley. It should also be noted that winter emissions of N_2O varied greatly from one year to another.

CO_2 was the most important gas in terms of the atmospheric impact of these organic croplands, being responsible, on average, for 78% of the total global warming potential (GWP), i.e. the sum of CO_2, N_2O and CH_4 with a 100-year time horizon (IPCC 2001). N_2O was responsible for about 22% of the GWP, and the effect of CH_4 was insignificant, less than 1%.

3.3.4. Conclusions

- The results of the research project indicate that emissions of carbon dioxide from abandoned organic croplands do not seem to decrease significantly with time after agricultural practices have ceased – the decomposition of drained peat evidently continues.

- The results further indicate that emissions of nitrous oxide from organic croplands can still be high even after 20–30 years of abandonment. Winter emissions account for a significant portion of the annual N_2O balance.

- Methane fluxes from the atmosphere into the soil may gradually increase after cultivation has ceased, but the slow deterioration in the ditch network may raise the water table level, which in turn may increase methane emissions. It should be noted, however, that methane emissions from abandoned organic cropland are of a marginal significance compared with the global warming potential of carbon dioxide and nitrous oxide emissions.

3.4. The effect of afforestation of organic croplands and cutaway peatlands on greenhouse gas balance

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3.4.1. Background

In Finland the afforestation of organic croplands and cutaway peatlands constitutes one of the most important means for creating carbon sinks set out in the Kyoto Protocol. Article 3.3 of the Kyoto Protocol allows for the use of land-use, land-use change and forestry measures (LULUCF) as carbon sinks. The most obvious effect of afforestation is the absorption of carbon by the growing trees. The changes in soil greenhouse gas fluxes are more difficult to estimate, and there are little research data on this.

The area of cultivated organic soils (soil organic matter content >20% of solid matter in soil) in Finland is nowadays about 300,000 hectares, which is less than half of the peatland area originally taken over for agricultural use (Myllys & Sinkkonen 2004). Large-scale afforestation of agricultural land, aimed at reducing the area under cultivation in the country, began in the late 1960s. Of the more than 240,000 ha of afforested agricultural land (Finnish Statistical Yearbook of Forestry 2004), the area on peatlands is estimated to be more than 80,000 ha. From the total area of 1,200,000 ha of peatland suitable for peat production in Finland (Virtanen & Hänninen 2004), annual peat harvesting nowadays covers 42,000 to 59,000 ha. Peat harvesting has already ceased on an area covering more than 20,000 ha (Selin 1999).

During agricultural use or fuel peat production, peatlands are efficiently drained. Continuous cultivation measures such as tillage and harrowing, fertilization, liming and addition of mineral soil change the properties of the peat soil substantially. In the afforestation of cutaway peatland, the nutrient imbalance is corrected by mixing mineral soil into the peat or by using fertilization. In both organic cropland and cutaway peatland the peat is well decomposed, and it has a high bulk density and nitrogen content. Organic cropland and cutaway peatland are significant sources of carbon dioxide (CO_2), as studies show.

Due to efficient drainage, organic croplands are minor methane (CH_4) sinks. The drainage may begin to deteriorate gradually after afforestation. After cultivation measures are ended, the aeration of the topmost peat layer may decrease, limiting tree growth and aerobic decomposition, especially if efficient drying is not provided for. Production of CH_4 may also increase in these areas.

In general, agricultural soils account for most of the global nitrous oxide (N_2O). Despite the fact that the area of organic croplands is small, they are estimated to account for 25% of the total anthropogenic N_2O emissions in Finland (Kasimir-Klemedtsson et al. 1997). Only scattered data on the effects of afforestation on N_2O fluxes from soil exist (cf. Maljanen 2001b).

Not much is known about the impact of afforestation on the greenhouse gas (GHG) balances of organic cropland and cutaway peatland. After afforestation, gradual changes in the soil structure, chemistry and biology may change the peat decomposition rate. Though the soil respiration rate is mainly regulated by soil temperature and moisture, also substrate properties can have substantial impacts on microbial activity in peat. Afforestation implies that the annual cycle of cultivating and harvesting crops is replaced by a much longer forest tree rotation. After afforestation, repeated soil amelioration measures such as tillage, fertilization and liming cease. These factors may change the soil properties into less favourable ones for the microbes and thereby lead to a slower decomposition rate of the organic matter and to reduced CO_2 and N_2O emissions. The gradual deterioration of the ditch network may lead to increased CH_4 emissions.

The aim of this study was to produce estimates of the annual soil CO_2, CH_4 and N_2O emissions from typical afforested organic croplands and cutaway peatlands, describe both the spatial and temporal variation in GHG fluxes caused by climatic factors, and examine annual variations in CO_2 emissions.

3.4.2. Material and methods

Study sites

Twelve afforested organic croplands planted with birch and pine were selected from four different locations in southern and central Finland (sites 1–8, 9–12). There were also six afforested cutaway peatlands (sites 13–18) in the peat harvesting area of Aitoneva in Kihniö (Figure 13). The sites were

Soil respiration measuring equipment on an afforested organic cropland (Photo: Mikulas Cernota).

Taking a gas sample using the snow gradient method in a planted stand of birch trees on a former organic cropland (Photo: Jyrki Hytönen).

selected to represent different tree species (pine and birch), afforestation age (10 to 43 years), tree stand volume (2 to 265 m^3/ha) and peat thickness (5 cm to 200+ cm). Mineral soil had been mixed into many of the organic croplands to improve the soil, and on three of the cutaway peatlands mineral soil had become mixed in the top peat layer in connection with afforestation. The peat bulk density was considerably higher in afforested organic croplands than on forestry-drained peatland.

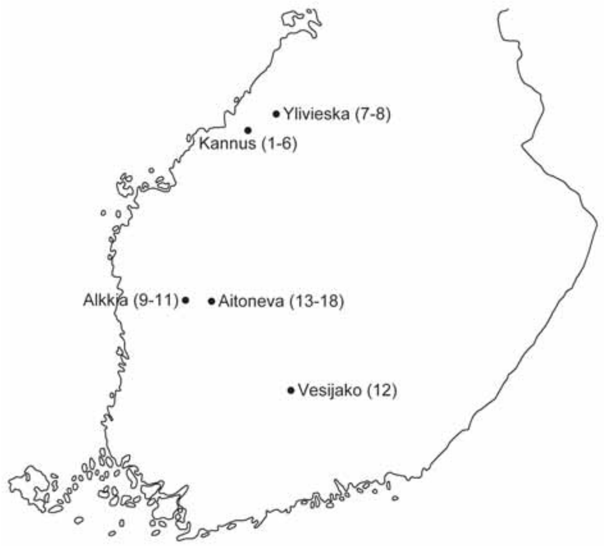

Figure 13. The locations of the study sites.

Soil CO_2 exchange measurements

At each study site, 2–8 sample plots were established to measure the heterotrophic CO_2 respiration of the peat ('old peat'), i.e. the respiration of the decomposers in the soil. An aluminium tube (Ø 31.5 cm) was inserted into the soil to a depth of 30 cm in order to exclude root respiration. The above-ground litter and surface vegetation were removed from the sample plots, and further accumulation of fresh litter was prevented by placing a net above the sample plot. To eliminate autotrophic plant respiration, the above-ground parts of green plants were removed by manual weeding and clipping. Measurements were carried out using a portable infrared gas analyser weekly during the growing season and monthly during the winter, depending on the site, for a period of two to three years between 2002 and 2005.

Statistical response functions were constructed between measured soil CO_2 emissions and simultaneously measured soil temperatures at a depth of 5 cm (cf. Mäkiranta et al. 2007). An average was separately calculated for wintertime measurements (November to April). Soil temperature at a depth of 5 cm was monitored continuously at all sites using electronic temperature sensors. The annual balances of CO_2 fluxes for each sample plot were calculated using the hourly soil temperature data and the equations devised.

Annual variation in soil CO_2 emissions

In order to study the year-to-year variation in soil CO_2 emissions caused by changes in weather conditions, a 30-year time span for soil temperature was generated for an afforested organic cropland site in Kannus. In order to generate the changing weather conditions, we adopted and modified a weather generator originally developed at the University of Joensuu as a part of the FINNFOR project. Annual soil CO_2 emissions during the 30-year time span were calculated separately for each sample plot. The average winter emissions for each sample plot were used for the winter season.

CH_4 and N_2O exchange

Square (58 x 58 cm) aluminium collars were used to delimit the permanent sample plots in Kannus, Ylivieska and Alkkia, and round collars (Ø 31.5 cm) in Vesijako and Aitoneva. During the snow-free periods, the fluxes of CH_4 and N_2O were measured every 2–3 weeks using 30-cm-high aluminium chambers equipped with a fan. Gas samples were drawn (4 samples over the 20- to 35-minute incubation time) into syringes and analysed using a gas chromatograph. During the winter, the gas fluxes were studied by measuring the gas concentrations in the snow by the snow gradient method (Maljanen et al. 2003).

3.4.3. Results

Soil CO_2 emissions

Annual soil CO_2 emissions at the studied afforested organic cropland sites varied from 207 to 539 g CO_2-C m^{-2} a^{-1} (Figure 14). The emissions were higher in the south (mean 480 g CO_2-C m^{-2} a^{-1}) than in the north (mean 314 g CO_2-C m^{-2} a^{-1}). The afforested cutaway peatlands emitted CO_2 within the range of 275 to 470 g C m^{-2} a^{-1}, the mean being 381 g C m^{-2} a^{-1}. The proportion of the annual emission emitted during the wintertime on all of the measured sites varied from 9% to 25%, the average being 16%.

Annual soil CO_2 emissions for a 30-year time span were simulated for site 6 (Kannus). Over the simulation period, the average annual emission on the site was 276 g CO_2-C m^{-2} a^{-1}, and when corrected for the 10% overestimation of the simulation process, the average emission is about 250 g CO_2-C m^{-2} a^{-1} (Figure 15). The simulated annual values ranged approximately 10% above and below the long-term average.

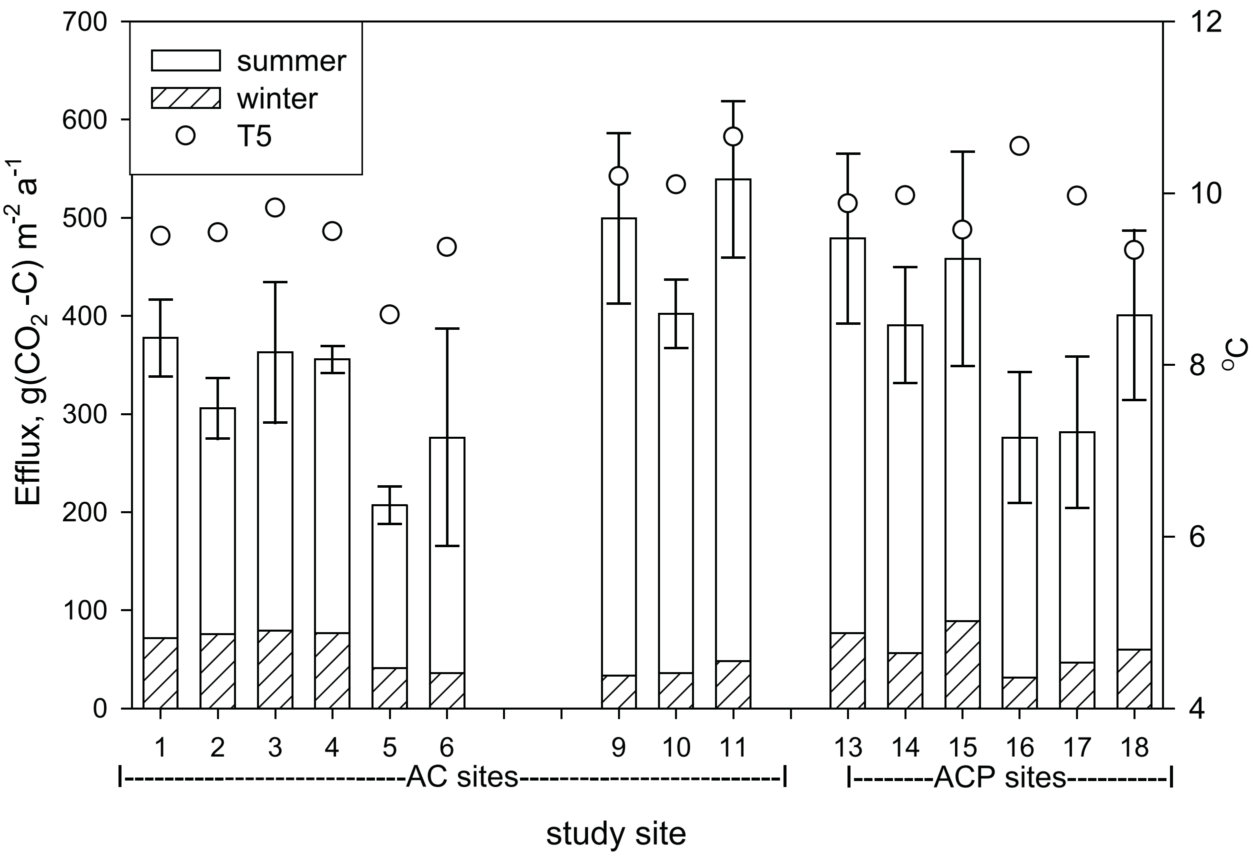

Figure 14. Annual CO_2 emissions from afforested organic cropland (AC) and afforested cutaway peatland (ACP) sites studied at the sample sites.

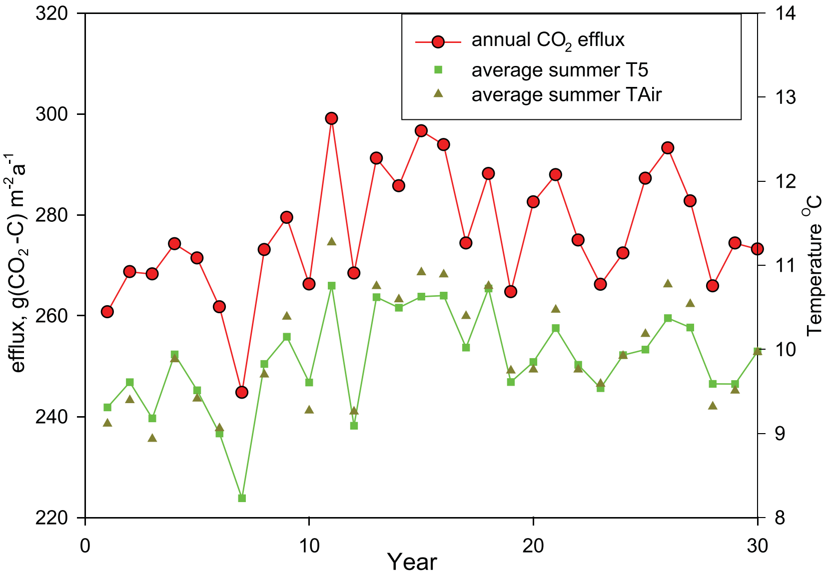

Figure 15. Variation in CO_2 emissions for a 30-year time span.

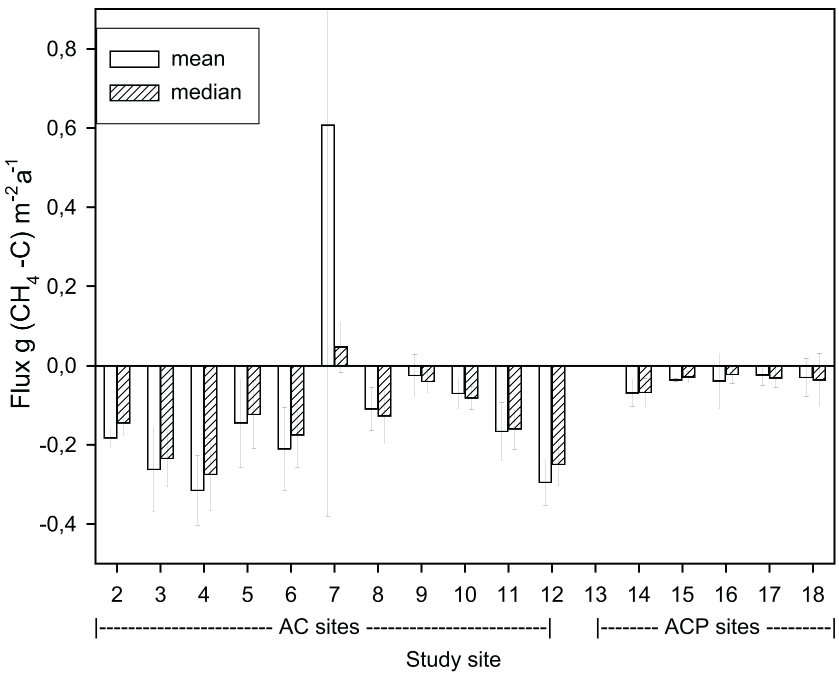

Figure 16. CH_4 emissions from afforested organic cropland (AC) and afforested cutaway peatland (ACP) sites studied. Fluxes converted to carbon (CH_4-C).

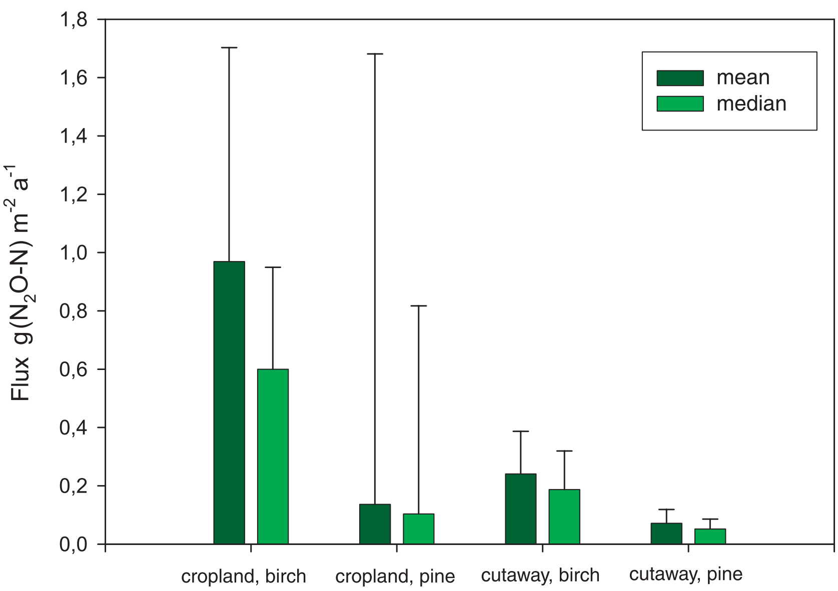

Figure 17. N_2O emissions from afforested organic croplands (AC) and afforested cutaway peatlands (ACP) afforested with birch or pine.

CH_4 emissions

Ten of the eleven afforested organic cropland sites were annually small sinks of atmospheric CH_4 (Figure 16). The annual CH_4 fluxes were about the same across the different regions. Site 7 demonstrated some brief periods of CH_4 emissions, which had a powerful impact on the calculated mean annual flux. The CH_4 uptake rate at the afforested cutaway peatland sites was slightly lower than at the afforested organic cropland sites.

N_2O emissions

All of the studied sites emitted N_2O (Figure 17). The annual emissions varied greatly between the sites. Annual N_2O emissions for the afforested organic cropland sites varied from 0.1 to 3.0 g N_2O-N m^{-2} a^{-1}. The emissions during winter were, on average, 42% of the annual emissions.

The mean N_2O emissions from the afforested cutaway peatland sites were lower than those from the afforested organic cropland sites. The annual N_2O emissions of the afforested cutaways varied from 0.01 to 0.48 g N_2O-N m^{-2} a^{-1}.

Tree species, stand age, stand height or volume, depth of peat or water table level were not strictly associated with the annual N_2O emissions rates. However, there was a correlation between top soil carbon-nitrogen (CN) ratios and the annual N_2O emission, the emissions of N_2O increasing exponentially with increasing CN ratios.

3.4.4. Discussion

Soil CO_2 emissions

The measured soil CO_2 emissions from the afforested organic cropland sites varied between 207 and 539 g CO_2-C m^{-2} a^{-1}. Since the bare soil CO_2 emissions from afforested organic croplands have not been reported previously, comparisons can only be made with agricultural and forestry-drained peat soils. The soil CO_2 emissions in this study were of the same magnitude as measured by Nykänen et al. (1995) on organic grassland in eastern Finland (392–401 g CO_2-C m^{-2} a^{-1}) but much lower than that on organic croplands in eastern and western Finland as measured by Maljanen et al. (2001a: 880–1,120 g CO_2-C m^{-2} a^{-1}; 2004: 690–790 g CO_2-C m^{-2} a^{-1}, respectively). Weather conditions, especially temperatures during the growing season, have a strong impact on soil CO_2 emission. This was demonstrated in this study by the 30-year simulations. During the actual measurement period, the average summer air temperature was 0.5 °C higher than the long-term average summer air temperature. Thus the annual measured soil CO_2 emission was probably also higher than the long-term average. Measurements on croplands were done in different weather conditions as well as different geographical locations. Taking weather factors into consideration, the soil CO_2 emissions after afforestation appear to be lower compared with soils in active agricultural use. Lower emissions may result because of reduced air content in soil after the cultivation has ceased, the absence of fertilization or liming and lower soil temperatures on the afforested sites caused by the shading effect of the growing tree stand. All these factors may have led to reduced microbial activity compared with cultivated croplands.

The soil CO_2 emissions on afforested organic croplands were of the same magnitude or slightly higher than the annual values reported from peatlands drained for forestry (Minkkinen et al. 2007a: 248–481 g CO_2-C m^{-2} a^{-1}). At the studied afforested organic cropland sites, the cultivation practices have greatly transformed the soil properties, and at almost all the sites the peat bulk density and ash content were considerably higher than on peatlands drained for forestry. Growing-season soil temperatures on organic cropland have been shown to increase with the amount of mineral soil added. Mineral soil addition increases the soil pH and nutrient content.

The soil CO_2 emissions at the afforested cutaways (average annual emissions 381 g C m^{-2} a^{-1}) were much higher than the emissions from bare peat surfaces in Aitoneva 20 years after abandonment (growing season emission being 52–110 g CO_2-C m^{-2} a^{-1}, Tuittila et al. 1999). The sites in this study had been vegetated (afforested) for over 20 years before soil respiration measurements. Apparently the growing vegetation has produced fresh carbon as a substrate for heterotrophic microbes, thereby directly increasing the soil respiration rate. At the beginning of the experiment, the present above-ground litter was removed, but undoubtedly some fresh carbon remained in the old peat layer. All afforested cutaway peatland sites were fertilized when afforested. This increase in the peat nutrient content may have accelerated the microbial decomposition activity and the decomposition rate of the organic matter compared with non-afforested cutaway peatlands.

In order to derive the net ecosystem carbon exchange (NEE) from the CO_2 emission of soil respiration, it is necessary to also consider the car-

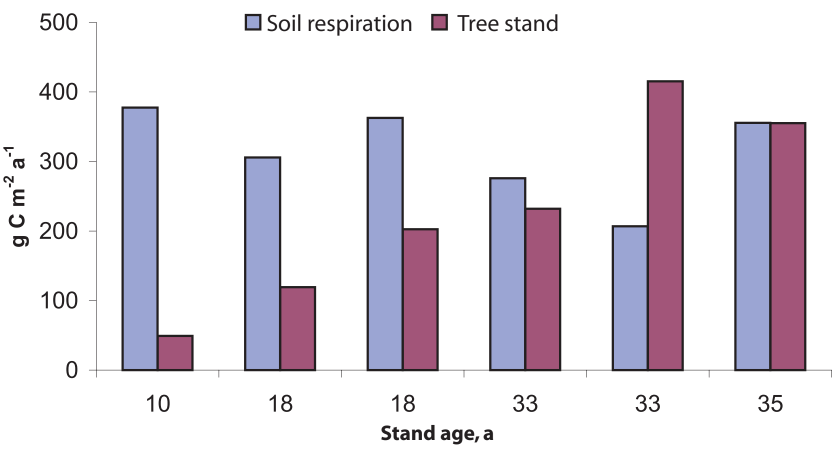

Figure 18. Annual heterotrophic soil respiration at afforested organic cropland sites and the carbon bound annually by tree growth over the measurement period.

bon input through photosynthesis and carbon output through leaching. When the carbon bound by the vegetation (mainly trees) is taken into account, the CO_2 balance of the site changes considerably. According to micrometeorological (eddy covariance) measurements, a 30-year-old pine stand growing on an afforested field was only a minor source of atmospheric CO_2 (50 g CO_2-C $m^{-2}a^{-1}$, Lohila et al. 2007). The tree stands at afforested organic cropland sites were measured twice in the course of the study. Biomass equations were used to calculate the annual production of biomass, which was then converted to carbon. A tree stand about 30 years old absorbed as much carbon as was released in soil respiration, or slightly more (Figure 18).

The results of this study indicate that on afforested cutaway peatlands, assuming a tree growth of 46–329 g CO_2-C $m^{-2}a^{-1}$, the soil CO_2 emission from soil respiration exceeds the carbon sequestration by tree growth, and therefore these areas primarily act as a net source of carbon into the atmosphere. However, it was found in this study that a birch stand in a rapid growth phase had absorbed an estimated 520 g m^{-2} of carbon per year in its above-ground and underground portions, which is slightly more than the emission from the heterotrophic soil respiration measured in a birch stand of similar size (390 g CO_2-C m^{-2} a^{-1}). Similarly, carbon sequestration in a 43-year-old stand of pine trees (270 g m^{-2} a^{-1}) was almost equal to the soil CO_2 emission (281 g CO_2-C m^{-2} a^{-1}).

CH_4 emissions

Afforested organic cropland sites acted mainly as minor sinks of CH_4, similarly to forestry-drained peatlands and peatlands under cultivation. Afforestation does not appear to change the soil CH_4 flux, provided that the drainage is adequate. Probably the high CH_4 emissions observed at one of the sites were caused by the poor drainage of the site, leading to anaerobic soil conditions. Since the drainage of afforested organic croplands has often been shown to be inadequate and the soil physical properties are generally rather unfavourable for adequate drainage, the risk of CH_4 emissions without ditch network maintenance after afforestation is likely.

The afforested organic cropland sites showed a slightly higher potential to serve as a sink of CH_4 than the afforested cutaway peatland sites. This may be due to severe growth conditions (i.e. large fluctuation in soil surface temperature, drought and unbalanced nutrient status), which is typical for cutaway peatlands for several years after peat harvesting has ceased. Also, the residual peat substrate in cutaway peatlands may be several thousands of years old, and thus microbe populations producing CH_4 may not have yet adapted to the prevailing new situation.

N_2O emissions

The soil's N_2O emissions from the afforested organic cropland sites were similar to those reported for cultivated organic croplands, but higher than those reported for forestry-drained peatlands. The afforested organic cropland sites had not been given any nitrogen fertilization after afforestation. The results support earlier findings that the afforestation of cropland on peat soils does not terminate N_2O emissions.

The afforested cutaway peatland sites appeared to have lower N_2O emissions than the former cropland soils. N_2O emissions at the afforested cutaway peatland sites were slightly higher than those reported for peat harvesting areas. The variation between the measured sites was high.

3.4.5. Conclusions

- This research project indicates that afforestation of former organic croplands considerably lowers the emissions of carbon dioxide (CO_2) created by the decomposition of peat. The reduction of soil CO_2 emission is due to the cessation of cultivation practices, which accelerate the peat decomposition processes during the active agricultural phase. Peat properties on afforested organic croplands differ considerably from forestry-drained peatlands, resulting in higher soil CO_2 emissions from afforested organic croplands than from forestry-drained peatlands. Mineral soil application, in particular, had an accelerating effect on the soil CO_2 emission on afforested organic croplands.

- The results show that afforestation of former peat harvesting areas increases the heterotrophic soil CO_2 emissions. The reasons behind this increase are 1) fertilization and soil preparation associated with afforestation, and 2) input of fresh carbon into the soil in the form of litter from the growing vegetation. These changes in the soil properties are likely to increase microbial activity and, consequently, heterotrophic respiration in the peat soil.

- Nitrous oxide emissions from the soil do not appear to change after afforestation of organic soil croplands, but they appear to continue at a rather high level.

- Methane emissions from the soil do not change after afforestation; rather, the areas remain minor sinks for methane.

- The afforestation of organic croplands decreases their greenhouse gas impact, particularly when the increased sequestration of carbon into the growing tree stand is taken into consideration. Afforestation of cutaway peatlands initially increases greenhouse gas emissions, but the sequestration of carbon by growing trees will, under favourable conditions, compensate for the emissions from the decomposition of old peat.

3.5. Ecosystem-level carbon sink measurements on forested peatlands

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3.5.1. Background and aim

Ecosystem-atmosphere carbon dioxide (CO_2) exchange includes both the CO_2 uptake by the vegetation and the respiration from vegetation and soil. The sequestration of carbon in trees above ground can be determined by measuring the growth of the tree stand, and soil respiration can be measured using the chamber method. However, at present the micrometeorological method is the only way of measuring an entire forest or peatland: the carbon sinks of the trees (roots included) and surface vegetation, and the components of soil respiration both above and below ground. The method produces continuous data on area-averaged CO_2 exchange and is considered a reference method in the study of ecosystem-atmosphere gas exchange. There are now hundreds of micrometeorological measurement sites in the world, from the Arctic areas to the tropics. It was only possible to maintain one measurement system in this research programme. The aim of this research project was to determine the ecosystem-level CO_2 balance on a forested drained peatland and on an afforested organic cropland. We have measured gas balances on an organic cropland and on pristine peatlands in other research projects, and these earlier data are used for comparison.

3.5.2. Material and methods

The two forested sites in the study were selected because they are particularly problematic for the use of the chamber method only. One was an afforested organic cropland site; the other was a forestry-drained peatland site. Measuring point locations of the study are shown in Figure 19. The Alkkia peatland in Karvia was cleared for agriculture in 1937 and planted with pine seedlings in 1971. After drainage, mineral soil was added into the soil. After the planting of the trees the area has been fertilized twice. The peat thickness was 1.5 m, and the tree height at the time of measurement was 12 m. Kalevansuo in Loppi was drained and fertilized in 1971. The peat thickness was 3 m, and the tree height was 10–16 m. Kuuma field in Jokioinen had been in cultivation for at least 100 years, and accordingly the peat thickness is no more than 0.6 m and the soil is beginning to resemble mull. The sedge fen sites in Kaamanen and at Siikaneva in Ruovesi were in a pristine state. The peat thickness was about 1 m at Kaamanen and 2 to 4 m at Siikaneva. The annual average temperature in Kaamanen is –1 °C, and the texture of the peat layer therefore somewhat resembles that of the palsa mires which occur further north. The growing season is longer at Siikaneva, and the annual average temperature is 3 °C.

Figure 19. Location of the measurement sites in the study.

The method used in this study was the micrometeorological method (also known as the tower method or the *eddy covariance* -method). The method is non-invasive and is based on measurements of how gases are transported to and from the ecosystem in the lowest part of the atmosphere. An anemometer is placed in a mast above

A pine stand at a dwarf-shrub type site in an old drained peatlands (Photo: Sakari Sarkkola).

the study site, and gas concentrations are measured using an analyser at the same location. Samples are taken 10 times a second, and the flux is calculated as a covariance between instantaneous fluctuations in the gas concentration and the vertical wind velocity. The measurements are taken automatically, and the system operates round the clock all through the year. The measurement represents an average for an area covering several hectares, i.e. it is an ecosystem-level measurement.

In this study, CO_2 fluxes were measured using the micrometeorological method, while nitrous oxide (N_2O) and methane (CH_4) fluxes were measured using the chamber method at the afforested organic cropland site at Alkkia and the forestry-drained site at Kalevansuo. The same methods were used at the control sites, except that at Siikaneva and Kaamanen the CH_4 fluxes were also measured using the micrometeorological method.

3.5.3. Results

Annual averages were calculated for the CO_2 flux time series, shown as g CO_2 m^{-2} a^{-1} (Figure 20). Annual averages were also calculated for N_2O and CH_4 and converted into CO_2 equivalents using the global warming potential (GWP) factor, which takes into account the radiative efficiency of each gas and its persistence in the atmosphere.

The greatest CO_2 emissions were produced by organic cropland under active cultivation. The CO_2 balance of afforested organic cropland was almost neutral. The pristine peatland in Kaamanen was a minor CO_2 sink, whereas Siikaneva was almost twice as large a sink. The forestry-drained peatland site in Loppi was a major CO_2 sink. CH_4 emissions at pristine sedge fens were quite high, considering their GWP. Drained peatlands had a low CH_4 balance, but N_2O emissions from soils in agricultural use were quite high.

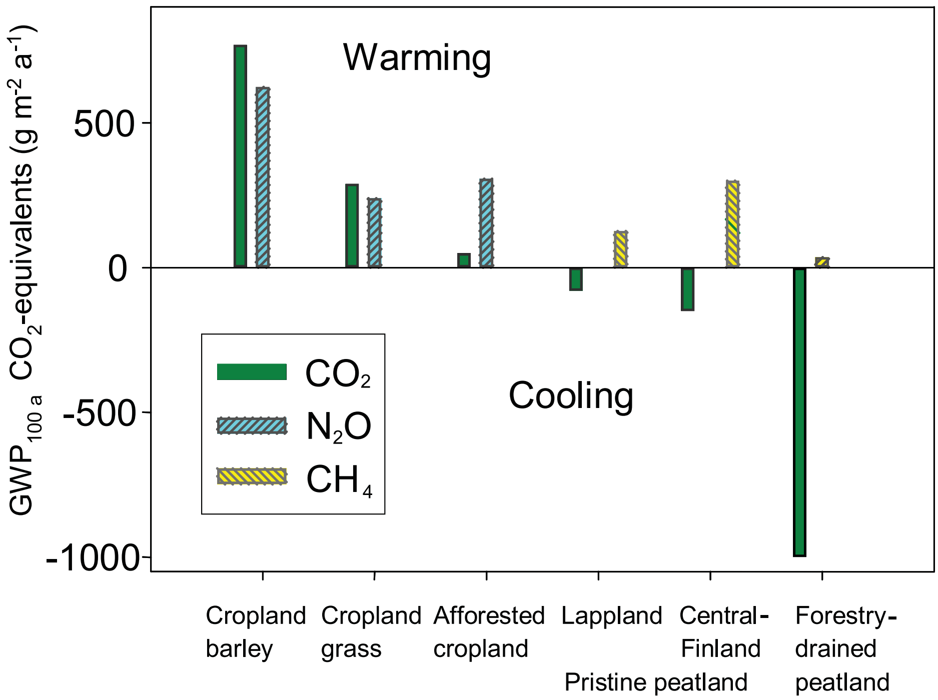

Figure 20. Peatland GHG balances at the measurement sites, by land use type.

3.5.4. Conclusions

- The forested sedge fens studied in this research project bound atmospheric CO_2 in roughly the same way as they have been doing on average for millennia. It was not found that climate change or any other external factor had caused any significant change to the carbon sink potential at these sites. The CH_4 emissions from pristine sedge fens are high enough to have warming effect on climate in 100-year time horizon.

- Organic cropland is a source of atmospheric CO_2 because of active peat decomposition. Direct emissions from a peat field can be curbed somewhat through grass cultivation rather than cereal cultivation, because the longer growing period means that the annual CO_2 emission is smaller. Organic cropland is a significant source of N_2O from the point of view of climate change; the global warming potential is of the same order as that of the CO_2 emissions.

- The results indicate that afforestation of organic cropland makes its net carbon balance much more favourable in terms of climate impact. At the measurement site in western Finland, the carbon sequestration by trees and surface vegetation compensated for the CO_2 emissions from active peat decomposition. The surface vegetation and litter dynamics constitute a carbon sink which cannot be observed merely through tree growth or soil respiration measurements. The highest climate warming impact in the afforested site is due to the emissions of N_2O; they are caused by cultivation and soil improvement measures affecting the nitrogen cycle.

- The results of the project indicate that a forestry-drained peatland area is a major carbon sink equivalent to a forest on mineral soil in its most rapid growth phase.

- In order to make the results more representative, it would make sense to include a pristine raised bog and different types of forestry-drained peatland in the measurements, which should be conducted over several years to illustrate annual variation. The study should include the entire growth cycle of the forest and also assess the climate impact of biomass removed from the forest or field.

3.6. Carbon gas exchange of re-vegetated cutaway peatland

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3.6.1. Background and aim

In Finland, peat is mainly harvested for energy production. During the harvesting, the peatland is drained and living vegetation and the peat layer accumulated over thousands of years is removed. In Finnish fuel peat harvesting practise most of the peat layer is removed, because the deep-lying sedge peat has greater energy content than the surface Sphagnum peat, which is more suitable for horticultural use. Peat harvesting leaves a cutaway peatland devoid of vegetation and unfavourable for natural re-vegetation. Such an area no longer binds atmospheric carbon dioxide (CO_2), but the residual peat gradually undergoes aerobic decomposition, which is why cutaway peatland is a net source of carbon into the atmosphere. However, unlike pristine mires cut-away sites no longer emit methane (CH_4). Indeed, in the absence of fresh organic matter, these dry areas may even be minor CH_4 sinks.

Restoration aims to create a new, functioning mire ecosystem resembling a pristine mire in terms of species composition and matter flows. Successful restoration, or re-wetting, leads towards an ecosystem that is a CO_2 sink and a CH_4 source. The first research results on this obtained in Finland indicate that a cutaway peatland site may begin to recover fairly quickly towards a functional peatland ecosystem, even before its vegetation resembles that of a pristine mire (Tuittila et al. 1999; 2000). This pioneering study was followed by several European and North American studies whose findings are in agreement (e.g. Waddington et al. 2003; Bortoluzzi et al. 2006).

Cutaway peatland with a shallow residual peat layer would seem to develop vegetation of sedge species, dominated by cottongrass (*Eriophorum vaginatum*) and various other sedges. These sedges typically have a high rate of carbon binding. The majority of litter from sedges ends up directly in an anaerobic environment. Because anaerobic decomposition evidently begins rather slowly after a prolonged dry period, young restored cutaway peatlands may be surprisingly effective carbon sinks. However, it is not known how long this period of efficient carbon sequestration lasts or even how general the phenomenon is. Peat production on a large scale did not begin until the 1970s, and cutaway peatland restoration is a relatively new form of land use. Thus currently there is not yet information available that would enable the assessment of the greenhouse impact of restored cutaway peatland over a longer period of time.

The purpose of this study is to assess the carbon gas exchange of restored cutaway peatland over a period of time longer than just the first few years after restoration. Three different approaches are used: 1) assessing carbon gas exchange during the growing season in relation to the vegetation abundance on cutaway peatland restored ten years ago, 2) assessing carbon gas exchange on peatlands where peat extraction ended 50 years ago, and 3) comparing the development of cutaway peatland with the early natural development of a pristine mire and studying carbon gas exchange in a chronosequence of mires at different stage of succession in the land uplift coast.

3.6.2. Material

We use material from two sites at Aitoneva (in western Finland). The first site is a cutaway peatland site restored ten years ago, in autumn 1994, and the second is a site where peat harvesting, using the block-cutting method, was discontinued about 50 years ago. Vegetation and carbon gas exchange were measured at the first site in 2003 and 2004 and at the second site in 2000 and 2001. Five sites in Siikajoki (on the coast of the Gulf of Bothnia) were selected to form a series ranging from a wet meadow about 100 years old in the first stage of paludification to a peatland about 2,500 years old. Vegetation and carbon gas exchange were measured at these sites between 2002 and 2005.

At all sites, carbon gas exchange measurements were conducted using the closed chamber method, which enables the study of variation within each site. Vegetation was studied by assessing the coverage of each plant species and by monitoring plant development during the growing season. Studying the vegetation was essential, because the plant colonization into the restored area is crucial to carbon absorption.

The 10-year-old site had acquired vegetation dominated by a variety of plant species. At the site we aimed to compare the carbon gas exchange be-

A re-vegetated old peat extraction area at Aitoneva in Kihniö. The peat used to be harvested using the block-cutting method. Harvesting was discontinued in 1948, after which mire plants – *Sphagnum* mosses and sedges – have taken over the area, rendering it into a functioning, peat-forming mire ecosystem (Photo: Mika Yli-Petäys).

tween different plant species and to quantify the relationship between mire vegetation cover and carbon gas exchange on restored cutaway peatland. Thus, in our sampling we chose the plots subjectively rather than placing them relative to the occurrence of different vegetation types. The sample plots were placed in four vegetation types, each with a varied vegetation cover. All together there were 19 sample plots. The data included three control sample plots without vegetation. In order to study the relationship of plant species to the water table level, we extended our sampling with 19 sample plots systematically placed close to the previously selected sample plots.

At the 50-year-old site, the sample consisted of five peat harvesting trenches, with three sample plots placed in each for the vegetation and carbon gas exchange measurements.

In Siikajoki, there were five study sites forming a time series, extending from emerging mire about 100 years old to a mire about 2,500 years old. Each site was provided with 8 to 12 sample plots for measuring vegetation and carbon gas exchange.

In the peat extraction trenches and the time series, our sampling covered the variation typical for each site in terms of moisture and vegetation.

3.6.3. Results

Cutaway peatland restored 10 years ago

At the 10-year-old restored cutaway site the vegetation had specialized: cottongrass *vaginatum* was predominant on dry plots, whereas bottle sedge (*Carex rostrata*) was predominant on plots where the water table was constantly close to the soil surface. Although *Sphagnum* had formed a dense layer only in moist conditions, some of the mosses had their highest abundance in the drier plots. Thus, over ten years the site had acquired populations of the plant species which were the best adapted in the moisture conditions occurring on any given plot. However, the plant cover was patchy, showing that the colonization process was still ongoing.

Photosynthesis correlated directly with the leaf area of the vegetation. Photosynthesis efficiency was the greatest in the sample plots which had both vascular plants and *Sphagnum* mosses, as opposed to plots which only had vascular plants (Figure 20). Similarly, photosynthesis controlled the ecosystem respiration during the growing season so that 50% to 75% of the CO_2 bound by the plants was re-released into the atmosphere. The impact of the water table level was apparent: Respiration accounted for considerably less of the photosynthesis on moist plots with *Sphagnum* (Figure 20). Also, the CH_4 flux during the growing season depended on the amount of new carbon bound by the vegetation. Unlike respiration, the CH_4 flux into the atmosphere was greater on moist plots (Figure 20). Although all plant stands were sources of CH_4, the proportion of plant fixed carbon that was released as CH_4 was lower than on a pristine sedge fen.

The net carbon exchange was positive in all plant stands during the growing season, i.e. they functioned as carbon sinks (Figure 21). The size of the

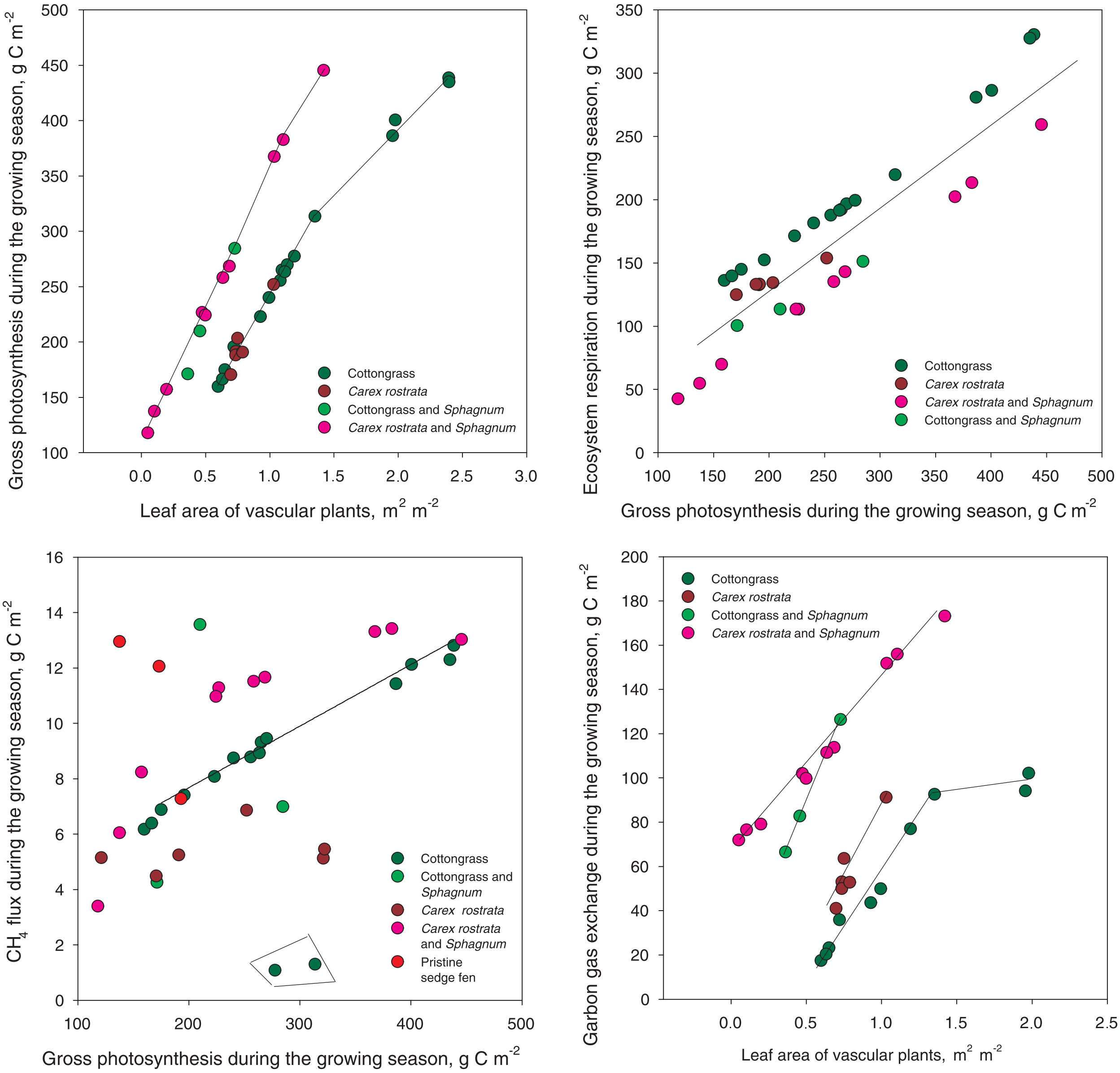


Figure 21. Carbon gas exchange during the growing season in different plant stands at a cutaway peatland site restored ten years ago. Top left: Photosynthesis in relation to the leaf area of vascular plants. Top right: Ecosystem respiration in relation to photosynthesis. Bottom left: CH_4 flux in relation to photosynthesis. The comparison is a made to a pristine sedge fen (Siikaneva, Ruovesi), whose vegetation resembles that of the 10-year-old restored cutaway peatland site. Two sample plots which were clearly drier than the others and where cottongrass (*Eriophorum vaginatum)* was growing differ clearly from the rest (circled). Bottom right: Ecosystem carbon gas exchange in relation to vascular leaf area. Positive figures indicate that the vegetation bound more carbon than it released.

carbon sink correlated strongly with the abundance of vegetation. In the young cutaway peatland, mixed plant stands of vascular plants and *Sphagnum* mosses were considerably more efficient carbon sinks than monospecies sedge stands. Bare peat surfaces released 20 to 71 g CO_2-C m^{-2} during the growing season, whereas sedge stands fixed 17 to 102 g CO_2-C m^{-2}, and mixed vascular plant and *Sphagnum* stands absorbed 67 to 173 g CO_2-C m^{-2}. Sedge plant stands released 1 to 9 g CH_4-C during the growing season; the figure for mixed plant stands was 3 to 14 g CH_4-C. Assuming that the CH_4 and CO_2 loss outside the growing season is 15% of the annual loss, the annual carbon balance would be –5 to 44 g C m^{-2} for sedge stands and 60 to 128 g C m^{-2} for mixed vascular plant and *Sphagnum* stands. Nearly all plant stands functioned as carbon sinks, but the mixed plant stands were more efficient.

Peat extraction trenches abandoned 50 years ago

The peat extraction trenches created by the block-cutting method had been fully colonized by mire vegetation. A new organic layer, 30 to 70 cm thick

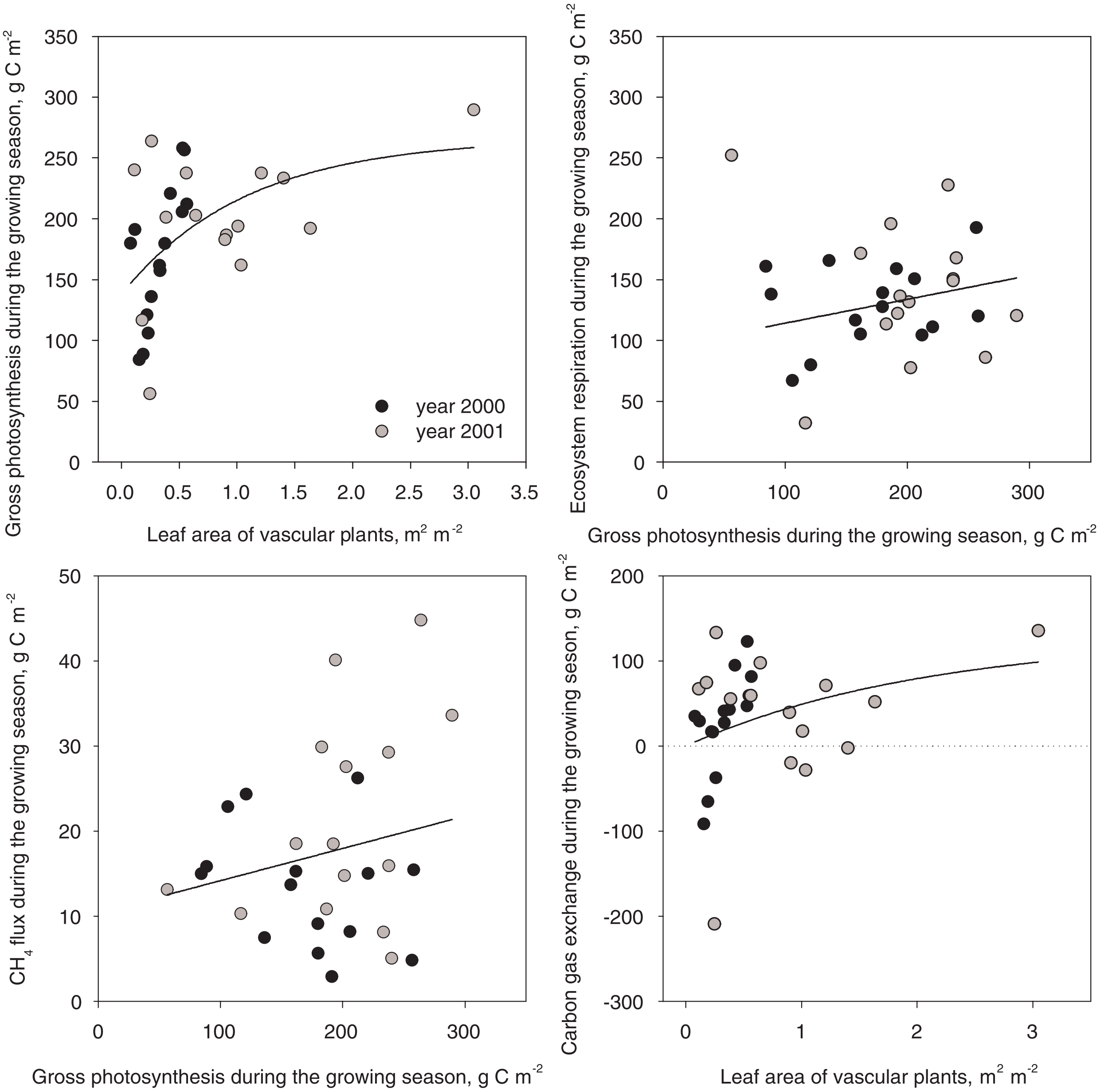


Figure 22. Carbon gas exchange during the growing season in peat extraction trenches 50 years after peat harvesting was discontinued. Top left: Photosynthesis in relation to the leaf area of vascular plants. Top right: Ecosystem respiration in relation to photosynthesis. Bottom left: CH_4 flux in relation to photosynthesis. Bottom right: Ecosystem carbon gas exchange in relation to leaf area. Positive figures indicate that the vegetation bound more carbon than it released; negative figures show a net emission.

consisting of *Sphagnum* mosses and vascular plant residue, had formed over the old peat. The vegetation was typical of oligotrophic sedge fens in the region, but there were also some fen species which are more common further north. The cover of vascular plants in the peat extraction trenches was the same or smaller than at the 10-year-old restored cutaway site (Figure 22), but all the sample plots had continuous *Sphagnum* moss cover.

The results on carbon gas exchange at the 50-year-old peat extraction trench site were somewhat puzzling. Unlike the developed vegetation and new organic layer would seem to indicate, the sample plots were minor carbon sources in both study years. Although the amount of carbon bound in photosynthesis during the growing season exceeded that released in CO_2 and CH_4 on most of the sample plots, three of the sample plots were a source of carbon into the atmosphere in both years even during the growing season. The CO_2 balance on the sample plots varied from –196 to 177g CO_2-C m^{-2}. The gross photosynthesis was lower here than at the 10-year-old site, but respiration was roughly the same (Figures 21 and 22). The CH_4 flux into the atmosphere was greater at the 50-year-old site than at the 10-year-old one (Figures

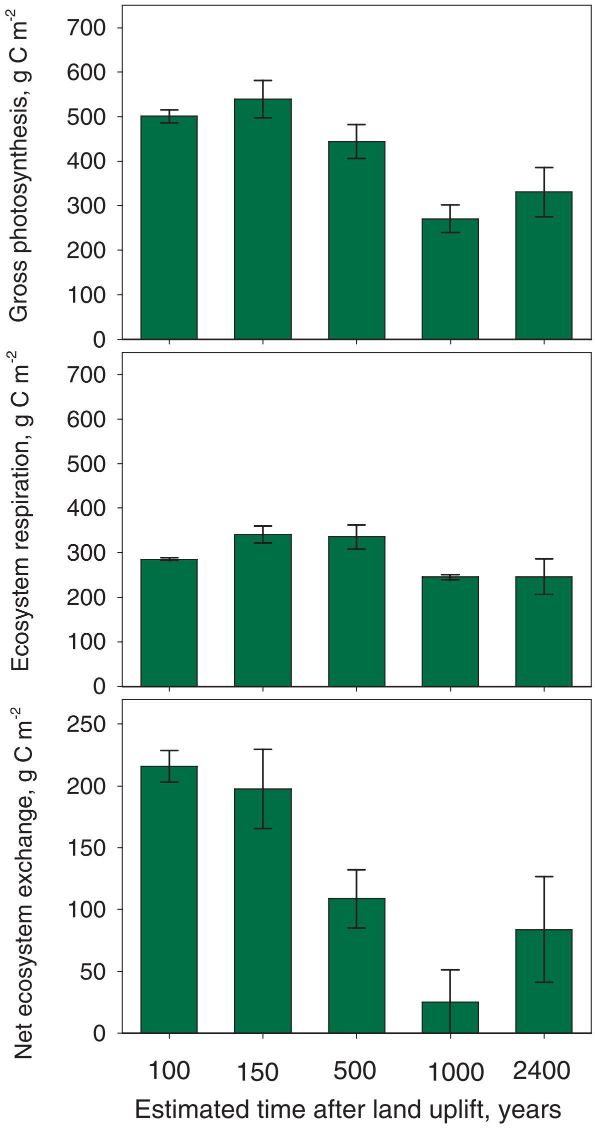


Figure 23. CO_2 exchange during the growing season in five pristine peatlands of different ages. The sites located in the land uplift coast of Bothnian Bay form a chronosequence from first stage of paludification to a fen-bog transition. Top: Photosynthesis (P_G). Middle: Ecosystem respiration (R_E). Bottom: Net ecosystem exchange (NEE). The vegetation fixed more carbon than was released.

21 and 22). The emissions of CH_4 into the atmosphere during the growing season totalled 3 to 87 g CH_4-C m^{-2}. Because of the weak gross photosynthesis and efficient decomposition, the average carbon balance in the growing season was only 32 g C m^{-2}. As the CO_2 loss during the winter is estimated at 44 g C m^{-2} and CH_4 loss at 5 g C m^{-2}, the annual carbon balance for the sample plots is –258 to 86 g C m^{-2}. In other words, the 50-year-old site released an average of 17 g C m^{-2} of carbon into the atmosphere per year

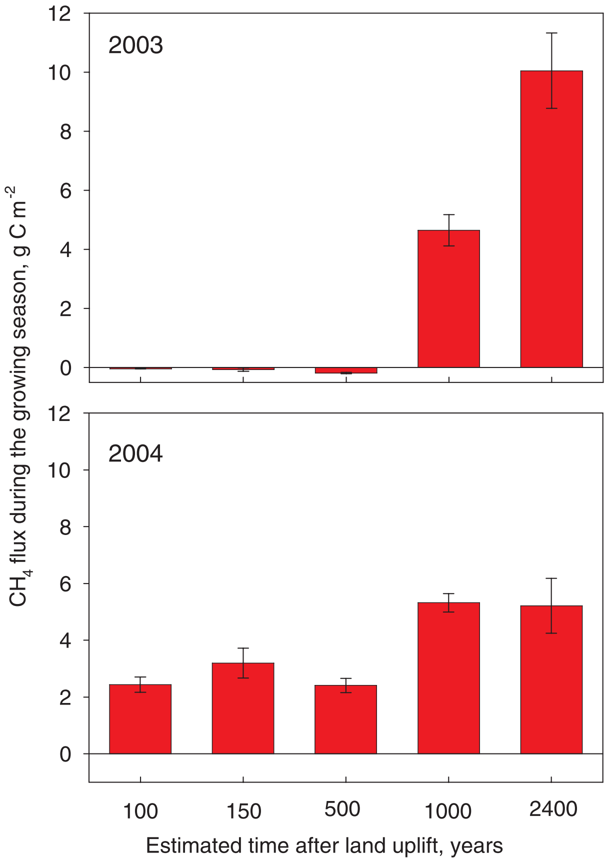


Figure 24. CH_4 flux during the growing season in five pristine peatlands of different ages in two different years. The sites located in the land uplift coast of Bothnian Bay form a chronosequence from first stage of paludification to a fen-bog transition. Positive figures indicate a CH_4 emission into the atmosphere, and negative figures indicate a net accumulation.

Time series of pristine mires

The youngest sites on the land uplift coast were wet meadows dominated by grasses and sedges, with very scarce moss cover. The two middle-aged sites (500 and 1,000 years old) were sedge fens with a continuous moss layer. The oldest site was in a transitional state between a sedge fen and a raised bog, where the vegetation is a mosaic of sedges and plant species typical of the late stages of succession. The average peat thickness at the three oldest sites was 50, 75, and 180 cm, respectively.

Net carbon binding during the growing season was the greatest in the youngest wet meadow, decreasing towards the older (1,000-year-old) sedge fen (Figure 23). By contrast, the oldest site, with a mixture of sedge fen and raised bog vegetation, was more efficient in binding carbon. The differences along the chronosequence were due to efficiency in photosynthesis, as there was little difference in ecosystem respiration between the sites. The net exchange at the youngest sites was the same or higher than that of the 10-year-old restoration site (Figures 21 and 23). The net exchange of the older sedge fen, by comparison, was of the same order as that of the 50-year-old peat extraction trenches (Figures 21 and 22).

There was great variation in CH_4 emissions along the time series (Figure 24). In the dry year of 2003, the three youngest sites were minor CH_4 sinks, while in the following two wetter summers they were net emitters of CH_4. The two oldest sites were CH_4 emitters in both years. For the time series as a whole, the CH_4 fluxes were the same or smaller than those measured at the 10-year-old restoration site (Figures 21 and 24).

3.6.4. Conclusions

- So far, the restoration succession of gaseous carbon exchange following peat extraction have been studied in Finland on one restored milled peat field and at one site where peat extraction using the block-cutting method was discontinued 50 years earlier. For the first site, the study covers the entire ten years of regeneration fairly well; this is the longest monitoring period in the world. For the second site, measurements were made during the growing seasons in two years.

- Results for the two restoration sites indicate that carbon binding restarts very rapidly with the return of mire vegetation. The carbon sink appears to become very efficient quite soon, particularly, because photosynthesis is effective and very little methane resulting from anaerobic decomposition is released.

- The most important factor for successful regeneration is sufficient soil moisture. Under favourable conditions, carbon binding may increase very rapidly, until the new organic matter approaches the edges of the area and the basin begins to fill in. Over time, carbon dioxide binding may slow down while the methane release processes stabilize, bringing the methane flux on the same level with that of pristine mires. However, the monitoring period is so brief that the figures are highly uncertain. On the other hand, results for the chronosequence where the mire development from an emerging mire 100 years old to a raised bog 2,500 years old was studied using the space-for-time approach support the conclusions that are based on a comparison between a 10-year-old and a 50-year-old restored peatland. In the chronosequence, gross photosynthesis was at its most effective at the youngest sites and decreased as the mire aged. Methane dynamics were also the most unstable at the youngest sites, whereas the older mires were steady emitters of methane. In the chronosequence, the paludification process was much slower than in cutaway peatlands restored by humans; without the intervention dry periods hinder the development.

- After mire vegetation had established itself, a restored cutaway peatland functioned like a pristine mire. The surfaces occupied by the mire vegetation acted as carbon sinks and methane emitters. Because there is a clear and strong correlation between net exchange and mire vegetation, vegetation characteristics could be used as a simple indicator for evaluating the carbon balance and methane emissions of a restored cutaway peatland.

- In order to speed up the regeneration process by introducing moss and vascular plants to the restored area, as is already being done on a broad scale in Canada, it is essential to introduce an ecologically wide variety of species so that a viable colony can be immediately established. A mixed plant stand seems to be capable of more effective carbon binding than a stand dominated by a single species.

- The greenhouse impact of pristine mires which is not directly the result of human activity is not included in the GHG inventory. Unlike pristine mires, restored cutaway peatlands are in a land use class that must be reported, even though that land use aims to alter the effect of human activity and to return the areas to their natural state. It would be logical to exclude such areas from reporting and to count them as pristine mires after a certain period of time has elapsed, i.e. when their vegetation has achieved sufficient coverage (e.g. half of the area).

4. Emission factors and their uncertainty in Finnish managed peatlands, and need for further research

Jukka Alm, Narasinha J. Shurpali, Kari Minkkinen, Jukka Laine

4.1. Background

The mobilization of the reserves of carbon and nitrogen sequestered in Finland's peatlands since the Ice Age, as the result of land use measures, causes emissions of greenhouse gases, viz. carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Peatlands have recently been identified as a central soil type in the definition of the EU COST 639 project because of their high organic matter content and the sensitivity of peat decomposition processes and carbon and nitrogen cycles to climatic conditions.

As a signatory to the UNFCCC, Finland is obliged to report on greenhouse gas emissions related to land use. In peatlands, it is particularly difficult to monitor changes in the carbon and nitrogen stocks in the soil when land use changes, because the emissions are minimal compared with the size of the stocks as a whole. Instead of changes in stocks, the IPCC Guidelines allow for reporting of the ecosystem-atmosphere exchange of greenhouse gases.

By the time the Finnish Programme on Climate Change (SILMU) was concluded in the mid-1990s, peatland researchers in various organizations had developed the methods and cooperation procedures required for gas flux studies. This laid the foundation for the study of the exchange of gases between pristine peatlands and, in particular, forestry-drained peatlands and the atmosphere. After the SILMU programme, gas exchange research expanded to the palsa mires (frozen mound bogs) of the north, organic croplands and the restoration of abandoned cutaway peatlands. However, there was no information on the gas balances of abandoned cropland (forested or non-forested) or afforested cutaway peatlands. Moreover, there was little knowledge of the gas fluxes of spruce peatlands and certain types of drained peatland. The research programme *Greenhouse Impacts of the Use of Peat and Peatlands in Finland* launched by the Ministry of Agriculture and Forestry, the Ministry of Trade and Industry and the Ministry of the Environment aimed at filling this gap. The detailed emission factors established in the research programme are described in this report.

For each gas, the overall level of the emissions from an ecosystem depends on factors related to the vegetation of the ecosystem, drainage, nutrient status and local climate. Although the research programme enabled significant gaps to be filled concerning emissions data for various types of land use, the geographical generalization of the findings proved more problematic than expected.

4.2. Material and methods

Gas exchange was studied during the time of year when the soil was not frozen, using the closed chamber method. In this method, a chamber is placed on an airtight collar installed in the surface peat. The chamber encloses the surface vegetation. Samples are taken from the airspace inside the chamber and analysed with a gas chromatograph to establish gas levels. It is usually possible to determine the CO_2 level on site. A transparent chamber is used to measure the net carbon exchange in the ecosystem under current light and temperature conditions. An opaque chamber reveals the total respiration of the ecosystem and enables the measurement of CH_4 and N_2O flows, too. At forest sites, autotrophic plant respiration was separated from heterotrophic soil respiration by removing the vegetation from within the collar. The accumulation of new litter from trees and surface vegetation was prevented by placing a net over the collar. In the winter, gas fluxes were measured by taking gas samples above and under the snow and by estimating the gas flow as a diffusion through a porous substance. The porosity of the snow was determined gravimetrically. The location of the research areas of the research programme is shown in Figure 25.

Simulation apparatus was developed for the regional calculation of emission factors. Based on weather statistics, it included a weather simulator and a database structure for managing regional research data and background variables such as weather data, models and the required parameter files. The weather simulator generates hourly weather data for a location at specified coordinates, and the simulator can be adjusted to illustrate new distributions of temperature and precipitation due to climate change, for instance. The weather simulator can be used with regionally representative regressive transfer function models to calculate regional emission factors for CO_2 and, possibly, to process models for N_2O at a future date.

In forests (peatlands and mineral soils), the information on carbon accumulation in the ecosystem

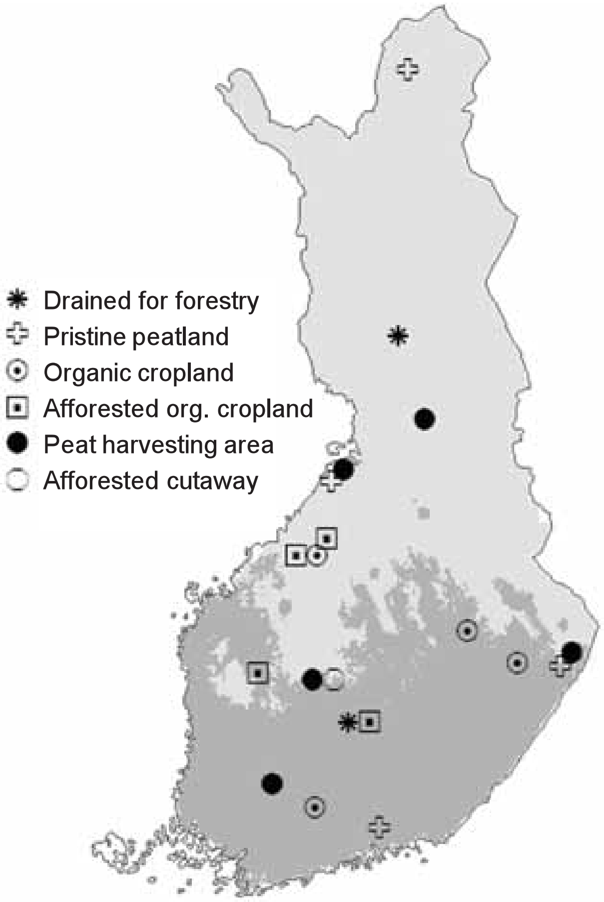


Figure 25. Research areas of the research programme by type of land use in Finland. The darker grey denotes the zone with a heat sum of more than 1,100 dd, calculated from the weather data for the period from 1961 to 1990.

is generated on the basis of terrain information collected by the Finnish Forest Research Institute (Metla) in the regional greenhouse gas calculation in the National Forest Inventory. The annual litter accumulation above ground and in the roots is generated for a tree stand using the terrain data, and the decomposition model shows what percentage of the litter will be left. The emission factor table enables the estimation for each gas of the decomposition rate for old litter and peat strata typical for each type of drained peatland forest. Examples of accumulation and emission figures for different types of drained peatland are given in section 3.2.3 (Figure 9).

4.3. Factors affecting emission factors in different types of peatland

Quantitatively, the major greenhouse gas emission consists of the CO_2 emitted when organic matter (litter and peat) in forestry-drained peatland is aerated. The aeration of old litter is the highest in nutrient-rich forest types such as herb-rich type and lowest in nutrient-poor forest types such as dwarf shrub type and *Vaccinium vitis-idaea* (lingonberry) type (Table 4). Most of Finland's forestry-drained peatlands are nutrient-poor or intermediate drained peatland types.

Table 4. Annual greenhouse gas (GHG) emissions from forestry-drained peatlands for different types of site (cf. Martikainen et al. 1993, Minkkinen et al. 2007a and Minkkinen et al. 2007b). The CO_2 emission figure only includes CO_2 released in the decomposition of organic matter (= soil respiration), not the carbon sequestered in the soil in litter production (cf. Figure 9). 'South' and 'North' refer to the temperature sum zones in Figure 1. nd = not determined. The total CO_2 equivalent is calculated using the 100-year conversion factor (GWP[CH_4] = 23; GWP[N_2O] = 296, Watson et al. 2001). Negative figures indicate a net influx from the atmosphere to the ecosystem. Site types: Vatkg = Dwarf-shrub type, Ptkg = Vaccinium vitis-ideaea (lingonberry) type, Mtkg = Vaccinium myrtillus (Blueberry) type, Rhtkg = Herb-rich type.

GHG	Vatkg	Ptkg	Mtkg	Rhtkg
CO_2, g m^{-2} a^{-1}				
South				
Average	880	975	1,250	1,713
Min–Max	719–1,001	810–1,096	1 045–1,404	1,437–1,911
North				
Average	nd	nd	1,749	nd
Min–Max			1,555–2,035	
CH_4, g m^{-2} a^{-1}				
Average	1.9	–0.27	0.21	–0.58
Min–Max	–0.3–3.5	–0.82–0.28	–0.20–0.87	–0.73– –0.39
N_2O, g m^{-2} a^{-1}				
Average	0.009	0.13	0.37	0.56
Min–Max	0–0.018	0.06–0.21	0.17–0.82	0.30–0.81
CO_2-equiv. g m^{-2} a^{-1}				
Total	926	1,007	1,614	1,865

Soil respiration is dependent on temperature and the moisture of the peat, enabling annual emissions to be modelled simply on the basis of the diurnal variation of weather factors. This is the basis for the estimated annual CO_2 at each test site. We assumed that the soil respiration of peatlands of the same type would be roughly similar in relation to temperature anywhere in the country. However, observations concerning a soil respiration temperature response higher in certain northern forestry-drained peatlands and peat harvesting areas than in southern areas added uncertainty to modelling CO_2 loss from peat. Annual emissions averages calculated for the test areas (Figure 25) have to be used as the emission factors. The planned use of regional weather data to generate more accurate regional emission factors will have to wait for more comprehensive soil respiration measurements.

Drained peatlands also produce CH_4 if the water table level is high, but measurements show that even at its highest the annual CH_4 emissions from sparsely forested nutrient-poor drained peatland are less than those of pristine raised bogs. Efficiently drained and afforested peatlands are often minor CH_4 sinks. Significant amounts of N_2O are only released on nutrient-rich or nitrogen-fertilized peatlands. Judging by the regional information on the carbon-nitrogen (CN) ratio in surface peat collected by the Finnish Forest Research Institute (Metla), forestry-drained peatlands could on the whole be a significant source of N_2O (3–4 Tg CO_2 equiv. a^{-1}), and preliminary calculations show that about half of the emissions come from densely forested spruce peatlands (see section 3.2, Figure 11).

Recent research has confirmed and further specified the data on significant CO_2 and N_2O emissions from organic croplands. The greenhouse impact of N_2O in the atmosphere can be as much as 296 times that of CO_2 in a 100-year time horizon (GWP_{100}). N_2O emissions are caused not only by the naturally extensive carbon and nitrogen stocks in peat but also, in particular, by the nitrogen boost that comes from fertilization. Although emissions are highly weather-sensitive, weather fluctuations can only help predict a small portion of emissions directly. Applying process models from gas exchange research in the temperate zone to the climate conditions of the boreal zone is difficult. New observations indicate that 25 to 60% of N_2O emissions occur in the winter. The biophysical mechanisms of winter emissions are only now being studied, and the most promising models are being developed in international cooperation. As for CH_4, organic soil croplands are minor sinks, because peatland in agricultural use has a low water table level, or they may be minor emitters when the peat gets wet and its oxygen content decreases.

With regard to organic croplands it should also be noted that the crops produced in the fields and then removed eventually also turn to CO_2 when consumed, and partly even to CH_4, as in the case of animal feed digested by cows. In abandoned organic croplands, gas emissions would seem to continue almost unchanged even decades after cultivation activities have ended (Table 5).

Afforestation of organic croplands and cutaway peatlands has been estimated to reduce their greenhouse impact, and new results would seem

Table 5. Annual GHG emissions from organic croplands. The minimum and maximum figures are the lowest and highest levels observed for each type of agricultural land. The combined CO_2 equivalent is calculated using the 100-year conversion factor (GWP[CH_4] = 23; GWP[N_2O] = 296, Watson et al. 2001). Negative figures indicate a net influx from the atmosphere to the ecosystem.

GHG	Average cropland	Grass	Cereal	Fallow	Abandoned
CO_2, g m^{-2} a^{-1}					
Average	2,072	1,485	1,760	2,971	1,188
Min–Max	290–4,033			2,167–4,033	–330–3,300
CH_4, g m^{-2} a^{-1}					
Average	0.42	1.27	–0.43	0.41	–0.22
Min–Max	–0.49–0.91	0.11–0.91	–0.49–0.51	–0.35–4.00	
N_2O, g m^{-2} a^{-1}					
Average	1.74	0.85	1.74	2.63	1.29
Min–Max	0.17–5.81	0.17–1.56	0.85–3.79	0.60–5.81	
CO_2-equiv. g m^{-2} a^{-1}					
Average	2,597	1,766	2,265	3,759	1,565

Table 6. Annual GHG emissions from the decomposition of peat and litter over 1 year old on afforested organic croplands and cutaway peatlands (carbon absorbed into the soil from litter not taken into account). The total CO_2 equivalent is calculated using the 100-year conversion factor (GWP[CH_4] = 23; GWP[N_2O] = 296, Watson et al. 2001). Negative figures indicate a net influx from the atmosphere to the ecosystem.

GHG	Afforested organic croplands	Afforested cutaway peatlands
CO_2, g m^{-2} a^{-1}		
Average	1,354	1,397
Min–Max	759–1,976	1,008–1,756
CH_4, g m^{-2} a^{-1}		
Average	–0.15	–0.05
Min–Max	–0.43–0.81	–0.09– –0.03
N_2O, g m^{-2} a^{-1}		
Average	1.02	0.15
Min–Max	0.16–4.71	0.02–0.75
CO_2-equiv. g m^{-2} a^{-1}		
Average	1,652	1,438

to support this. For example, a 30-year-old pine tree stand in a rapid growth stage planted in an afforested organic cropland showed only a minor net emission of CO_2, 50 g CO_2 m^{-2} a^{-1} during the study year 2002–2003.

However, the results show that the emissions from the soil do not decrease so much that the carbon absorbed by the trees would necessarily make the overall balance positive. Also, afforested organic croplands would seem to be emitters of N_2O (Table 6).

4.4. Gas emissions from peat harvesting and after-use of peat harvesting areas

New information was gained on gas emissions from peat harvesting areas and stockpiles during the research programme. Most of the gas fluxes measured were of the same magnitude as the few earlier results available (Table 7), but there were some surprises too. The anomalously temperature-dependent CO_2 emissions in northern peatlands referred to above were observed at a test site in Pudasjärvi, but it was the measurements conducted at Aitoneva in Kihniö in two consecutive unusually warm and rainy years (2004–2005) that gave the greatest surprise. Under exceptional circumstances, a peat field can release unusually large amounts of CO_2 (Figure 26).

Table 7. Annual GHG emissions from milled peat fields and stockpiles (cf. Ahlholm & Silvola 1990, Nykänen et al. 1996, and Kari Minkkinen & Niko Silvan, Research Programme). Summer (May to October) and winter (November to April) emissions are itemized. The combined CO_2 equivalent is calculated using the 100-year conversion factor (GWP[CH_4] = 23; GWP[N_2O] = 296, Watson et al. 2001). The annual maximum includes the measurements at Aitoneva in Kihniö in the exceptionally warm and rainy summer of 2005, but these are not included in the calculation of the simulated annual average[a)].

GHG	Peat fields	Stockpiles
CO_2, g m^{-2} a^{-1}		
Average (summer)	663	15,260
Average (winter)	278	25,074
Entire year	695–4,101[*)]	
[a] Simuloitu		
Tampere	980 [b]	
Oulu	945 [b]	
CH_4, g m^{-2} a^{-1}		
Average (summer)	6.06 b	0.56
Min–Max	0.32–9.09	0.08–6.38
Average (winter)	1.17	38.61
Entire year	7.23	19.48
N_2O, g m^{-2} a^{-1}		
Average (summer)	0.26 b	0.34
Min–Max	0.06–0.50	0.20–0.48
Average (winter)	0.05	0.08
Entire year	0.31	0.42
CO_2-equiv. g m^{-2} a^{-1}		
Total	1,179	15,772 [c]
		769 [d]
		1,299 [e]

[a] Simulated emissions are based on a shared temperature-response function.
[b] Ditch emissions added as per Nykänen et al. (1996).
[c] Average of summer and winter emissions, assuming the stockpiles to be in place all year.
[d] Assuming that 10% of the peat field is reserved for stockpiles, in place during the summer (6 months).
[e] Assuming that 10% of the peat field is reserved for stockpiles, in place during the winter (6 months).

In afforested cutaway peatlands, the annual CO_2 emissions produced as the peat and old litter decomposed were the same as or larger than in forestry-drained peatlands. Subtracting the annual amount of carbon bound in the growing trees from the soil CO_2 emissions, assuming annual growth to be 46–329 g m^{-2} of carbon, the CO_2 balance of the ecosystem as a whole probably remains positive. However, afforestation does slow down carbon emissions for at least a few decades as the trees and the underground biomass grow (Figure 27).

Figure 26. The white and black symbols represent CO_2 measurements at different peat harvesting areas in Finland. The measurements are included in the regression model where soil respiration is associated with the temperature of the peat at a depth of 5 cm. The grey symbols represent measurements at Aitoneva in Kihniö in the unusually warm and rainy summer of 2005. The large open square and error margins depict the average CO_2 emission (0.88 g m^{-2} h^{-1}) and the average temperature at a depth of 5 cm (13.6 °C), and also the standard deviation of both variables. These anomalous measurements are not included in the CO_2 transfer function model for peat fields.

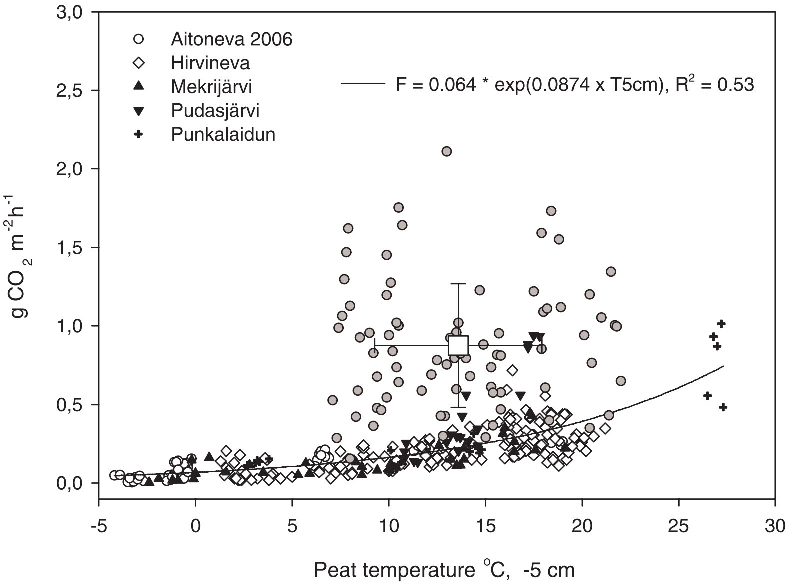
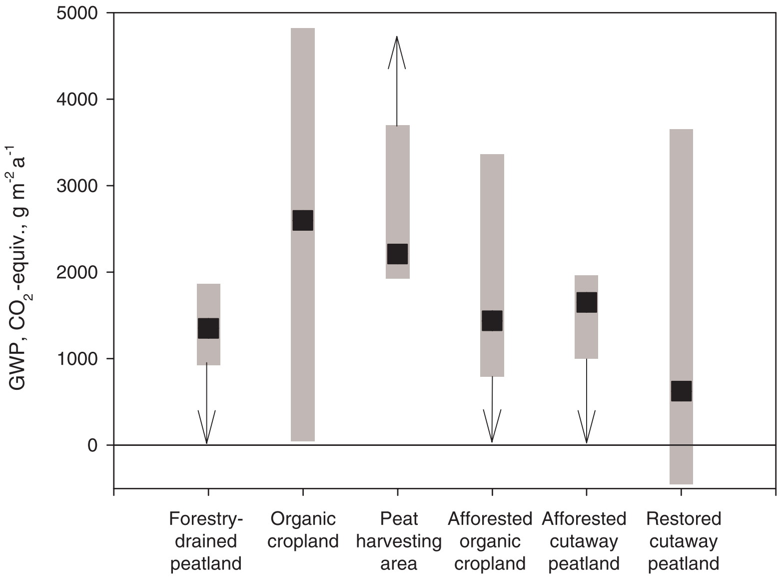


Figure 27. Summary of GHG emissions from the soil as CO_2 equivalents, for different types of use of peatlands. The figures are drawn from Tables 3 and 5–7. The bars indicate the ranges observed for each type of land use, and the black square denotes the average. The emissions from forestry-drained peatlands depend on the distribution of sites in Finland, and no best estimate can be given here. The downward-pointing arrows indicate the binding of carbon to first-generation trees, surface vegetation and undecomposed litter, mitigating the warming potential. The upward-pointing arrows indicate the increase in warming potential that may be caused by warm and rainy conditions, increasing CO_2 and CH_4 emissions in milled peat fields and stockpiles (Table 7).



Restoration of cutaway peatlands, or re-wetting, as a form of after-use for peat harvesting contributes to binding CO_2 in a long-term stock, but it also restarts CH_4 emissions as the peatland begins to regenerate. Restored peatlands become carbon sinks within a few years as long as the water table level is kept at the surface peat layer. The CH_4 emissions follow the binding of new organic matter with a delay. Compared with a pristine sedge fen, which is the target state, an area being restored may at first produce less CH_4 than a sedge fen even for many years. However, a restored area accumulating new plant biomass particularly rapidly could, under the right conditions, produce an exceptionally large annual emission of CH_4, more than 30 g CH_4 m^{-2}. Even such an ecosystem can calm down and its peat accumulation rate and CH_4 emissions decrease with time, as its resources shrink. Restoration should be regarded as a temporary change of land use, and it should be possible to eventually exclude the restored peatland from the greenhouse gas inventory, just like all pristine peatlands.

4.5. Outlook

The level of CO_2 loss from peat in forestry-drained peatlands in different areas constitutes one of the greatest uncertainty factors in the greenhouse gas inventory related to land use. A regional research project entitled *Monitoring system for carbon balances in forestry-drained peatlands – predicting* *and monitoring under changing circumstances* has been launched jointly by the University of Helsinki and the Finnish Forest Research Institute (Metla). The project is intended to collect systematic gas measurements from the same National Forest Inventory test sites for which data on the quality of the surface peat and on vegetation are already available.

It is a fact that emission factors are dependent on the climate. As the climate changes, the static emission factors given now will quickly become outdated. Developing a suitable model requires the gathering of comparative data on both environmental conditions and gas fluxes.

Distinguishing between soil respiration factors, autotrophic plant respiration and the CO_2 generated by heterotrophic life forms is challenging, especially in the case of peatlands. Analysing the percentages of permanent and radioactive isotopes of carbon in the various fractions of litter and humus may shed more light on this. For the time being, the predictability of N_2O fluxes is poor, and the fact that N_2O emissions occur in winter make the development of models a challenging task.

The problems involved in greenhouse gas emissions inventory apply to the whole of Europe and, accordingly, COST projects to improve cooperation among scientists and other integrated projects (including COST E21, E43, 639, Carbo-Europe IP, Nitro-Europe IP, BIOSOIL) have been launched in recent years. Harmonization of inventory methods requires the development of methodological potential in parallel in the old and new EU Member States.

Many major European research projects focus on the temperate zone and ignore the boreal zone. There is a lot of peatland in northern Europe: about one third of all the peatlands in the EU can be found in Finland, and one quarter in Sweden. Peatland is used to a considerable extent in Finland. Initial estimates on the carbon sink potential of forests show that forestry-drained peatland is a net emitter of CO_2 and thus reduces the carbon sink effect of the forests. Because of this, resources should be allocated particularly in Finland and Sweden to addressing the special issues of northern areas.

4.6. Conclusions

- This research programme helped to fill significant gaps in information on emissions related to various types of land use and to specify their emission factors. The total carbon emissions from any ecosystem depend, for each gas, on the vegetation of the ecosystem, drainage, nutrient status and local climate. Geographical generalization of the results proved more problematic than expected.
- The temperature-dependence of soil respiration varies from one part of the country to another, which contributes to uncertainty in predicting carbon dioxide emissions.
- Forestry-drained peatlands and organic croplands are, as a rule, methane sinks, only turning into a source if the peat gets wet and its oxygen content decreases.
- Forestry drainage contributes significantly to emissions of nitrous oxide. Nutrient-rich heavily forested spruce peatlands are the greatest emitters.
- Afforestation of organic croplands and cutaway peatlands reduces greenhouse gas emissions, but the trees are not enough to convert the area into a carbon sink.
- There is great annual variation in gas emissions from peat fields. Under favourable circumstances, such as warm and rainy weather, they may emit considerable quantities of carbon dioxide.
- Restoration of cutaway peatlands as a form of after-use following peat harvesting binds carbon dioxide into a long-term sink, but as the new peatland begins to evolve, methane emissions restart. Later, the peat accumulation rate and methane emissions even out. Restoration should be regarded as a temporary change in land use, and it should be possible to exclude the restored peatland, after a suitable interval, from the greenhouse gas inventory, just like pristine peatlands.

5. Greenhouse impact due to different peat fuel utilization chains in Finland – a life cycle approach

Johanna Kirkinen, Ilkka Savolainen

5.1. Background and aim

Peat is an important domestic fuel in Finland. The share of peat fuel in total primary energy production in 2004 was about 6%. Peat is used especially in medium-sized combined heat and power plants (CHP) for the needs of industry and municipalities. Peat is also an important auxiliary fuel in the use of other biomass for energy production, particularly wood. Because peat is a domestic fuel, it contributes to energy self-sufficiency and employment. Finland is highly dependent on imported energy sources such as oil, coal and gas. In the 1970s, after the oil crisis, a strong expansion of the use of peat fuel started as a measure to reduce dependency on imported fuels. Peat fuel production fields are mainly located in the central and northern parts of Finland, where their impact on local employment is important.

Using peat for energy causes greenhouse gas emissions. These emissions have grown with the increasing peat combustion. On the other hand, Finland's peatlands produce peat at a higher rate than we are using it. In Finland, peat is classified as a slowly renewing biomass fuel. All Parties are required to make an inventory of greenhouse gas emissions and to report on it to the UNFCCC. Finland's greenhouse gas inventory and emissions trading consider peat as parallel to fossil fuels. With the progress of emissions trading, peat production is expected to decrease, especially in condensate electricity production. Under the 2006 IPCC Guidelines, peat is to be reported in a class of its own, separate from fossil fuels, although peat is still equated with fossil fuels for the purpose of calculating emissions.

The purpose of the greenhouse gas inventory under the UNFCCC is to present the actual anthropogenic greenhouse gas emissions and sinks during the report year as accurately as possible. This enables the monitoring of actual trends in greenhouse gases and assessment of meeting the commitments under the Kyoto Protocol. Life cycle assessment of greenhouse impacts takes into account all the effects of emissions and sinks in the long term.

The aims of this study are 1) to find the most climate-friendly peat fuel production chain, considering the whole life cycle (i.e. what kind of areas peat fuel production should be directed to and what kind of after-use of cutaway peatlands would be the most climate-friendly), 2) to assess the sensitivity and uncertainty of the results, 3) to compare the greenhouse impact of the energy use of peat with that of the fossil fuels (mainly coal), and 4) to produce new information concerning the energy use of peat for the reporting of greenhouse gas emissions. Moreover, the aim is 5) to explore the greenhouse impact of peatland utilization chain in the case of using cutaway areas for producing renewable bioenergy (wood biomass or reed canary grass).

5.2. Assessment of greenhouse impact for the peat fuel life cycle

The greenhouse impact in the atmosphere can be expressed in terms of radiative forcing. Radiative forcing describes the perturbation of the radiation balance of the Earth, and it can be seen as the driver of global warming. Radiative forcing is assessed on the basis of the calculated changes in the levels of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) caused by the emissions and sinks involved in the use of peat for energy. The results are given either per petajoule (PJ) of energy produced, or as a dimensionless unit (E_{abs}/E_{fu}), which is equal to the cumulative radiative forcing caused by the life-cycle emissions and sinks divided by the energy of the fuel. This simplifies the greenhouse impact comparison between the various peat utilization chains and coal utilization chains. The life cycle greenhouse impact of fuel peat is examined from the perspective of the atmosphere. The gas fluxes into the atmosphere are emissions and are shown as positive figures, while the gas fluxes from the atmosphere are sinks and are shown as negative figures. In this study, life cycle analysis is used to examine the environmental impact (or climate impact, for the purposes of this study) of a function or product '*from cradle to grave*', from the first use of natural resources to waste management (ISO 14040 1997) and, in the case of peat, to after-use of the cutaway areas.

Even pristine peatlands have a greenhouse impact. This must be taken into account when considering the greenhouse impact of peat fuel utilization: when an area is taken over for peat production, its natural emissions cease. Therefore, the greenhouse impacts of the considered activity, production and combustion of peat fuel, are calculated by subtracting the emissions of the non-

Pristine sedge fen in southern Finland (Photo: Sakari Sarkkola).

utilization case from the case of peat fuel utilization (emissions from the peat field, stockpile and machinery):

$$I = I_U - I_R \quad (1)$$

where I is the net greenhouse impact, I_U is the greenhouse impact of the peat fuel (and biomass) utilization chain, and I_R is the greenhouse impact of the pristine peatland (or other peatland), i.e. the reference case.

5.3. Peat utilization chains examined

There are three phases in each utilization chain: initial state, peat fuel production (including machinery emissions, storage and transport to the power plant) and combustion, and after-use of the cutaway area. The initial states (i.e. peat fuel production areas) considered in this study are: pristine sedge fens; forestry-drained peatlands; and organic croplands. A sedge fen was chosen over other pristine peatlands because it is best suited for peat production. Sedge fens are also used more often for peat harvesting in Finland than raised bogs. About 25% of all peatlands taken over for peat harvesting have been pristine peatlands. Most (c. 75%) of the peatlands used for peat harvesting in Finland have originally been drained for forestry. Because forestry-drained peatlands have a great peat potential, it is important to study their greenhouse impact. The area of organic croplands (mull and peat) in Finland is approximately 300,000 ha, and about 67,000 ha of this are suitable for peat production. Organic croplands are significant emitters of gases, so the greenhouse impact of taking them over for peat production is worth investigating. At the moment, organic croplands are used very little for peat production. The after-use options for the harvesting area after the peat has been cut away and burned include restoration, afforestation or reed canary grass cultivation. Afforestation and cultivation of reed canary grass are particularly interesting options, because the growing biomass binds CO_2, and the biomass produced can be used as a raw material for industry or as an energy source.

The study examines the greenhouse impacts of 12 peatland utilization chains (Tables 8–9). The chains in Table 8 focus only on the greenhouse impact from the use of peat for energy production. The input data for the calculations are mainly derived from the measurements and expert evaluations conducted in the *Greenhouse Impacts of the Use of Peat and Peatlands in Finland* research programme (Table 11).

Table 8. Peat utilization chain options. Chains 5 and 6 illustrate production chains involving new peat harvesting method. Only the energy in the peat itself is taken into account in these chains.

Chain	Production reserve	Production	After-use	Reference state
1	Pristine peatland	Peat harvesting and combustion	Restoration	Pristine fen normal development
2	Pristine peatland	Peat harvesting and combustion	Afforestation	Pristine fen normal development
3	Forestry-drained peatland	Peat harvesting and combustion	Afforestation	Forestry-drained peatland normal development
4	Organic soil cropland	Peat harvesting and combustion	Afforestation	Organic cropland normal development
5 Vision chain A	Forestry-drained peatland	Advanced peat harvesting and combustion	Afforestation	Forestry-drained peatland normal development
6 Vision chain B	Organic cropland	Advanced peat harvesting and combustion	Afforestation	Organic cropland normal development

Table 9. Peatland utilization chains. The chains take into account the energy of the peat and the renewable energy from the after-use of the cutaway area (wood biomass, reed canary grass). Chains C and F represent peat fuel production chains employing new peat harvesting methods.

Chain	Production reserve	Energy production and combustion	After-use	Later use of peatland	Reference state
A	Forestry-drained peatland	Normal production (harvested peat) and combustion	Afforestation	Wood biomass energy use	Forestry-drained peatland normal development
B	Forestry-drained peatland	Normal production (harvested peat) and combustion	Reed canary grass cultivation	Reed canary grass energy use	Forestry-drained peatland normal kehittyminen
C	Forestry-drained peatland	Advanced production (new peat production method) and burning	Afforestation	Wood biomass energy use	Forestry-drained peatland normal kehittyminen
D	Organic cropland	Normal production (harvested peat) and combustion	Afforestation	Wood biomass energy use	Organic cropland normal development
E	Organic cropland	Normal production (harvested peat) and combustion	Reed canary grass cultivation	Reed canary grass energy use	Organic cropland normal development
F	Organic cropland	Advanced production (new peat production method) and burning	Reed canary grass cultivation	Reed canary grass energy use	Organic cropland normal development

The reference state for the production chains is maintaining the status quo. Chains 1–4 are considered the most common, illustrating differences in greenhouse impacts of the use of peat for energy between the chains. We also study two peat fuel production chains termed the vision chains, A and B (chains 5 and 6), illustrating the lowest possible greenhouse impact achievable by using new technologies and by directing production to areas which at the moment are sources of greenhouse gases (organic croplands and forestry-drained peatlands).

Peatland utilization was also considered more comprehensively, taking into account both the peat fuel produced and the use of the bioenergy produced in the after-use (afforestation or cultivation of reed canary grass) (Table 9). In these chains, production is directed to areas which are already sources of greenhouse gas emissions. After-use options are afforestation or cultivation of reed canary grass. The biomass obtained from the after-use (wood biomass, reed canary grass) is used for energy production. The impact of new peat harvesting methods is also represented in these chains.

5.4. Input data for calculations

Peat fuel

A pristine sedge fen is a CO_2 sink and a source of CH_4. Forestry-drained peatland is considered a source of CO_2 because of the increased rate of aerobic decomposition of peat. Organic cropland is a strong source of CO_2 and N_2O but a minor sink of CH_4. Peat fuel production areas release CO_2 and CH_4. Production fields and stockpiles (storage heaps) release CO_2 due to the decomposition of peat. Working machines release CO_2, but the combustion phase of peat production releases nearly 90% of the total CO_2 emissions of peat utilization. The combustion phase is also a source of N_2O emissions and CH_4 emissions. In the utilization chains which incorporate the use of the peatland first for peat harvesting and then for the production of renewable bioenergy, the emissions caused by the production and use of that bioenergy are also taken into account.

In after-use of the peat harvesting area, restoration has a similar greenhouse impact as a pristine fen. Afforestation causes carbon to be absorbed by the growing biomass (mainly trees, and litter above and below ground). Residual peat is usually left in peat production areas because of the unevenness of the bottom of the peatland. The decomposition of the residual peat is a significant source of CO_2 emissions, which is estimated to decrease gradually as the carbon stock in the soil decreases and the organic matter turns into matter that decomposes less easily. The assumption in this study is that the amount of residual peat is a layer about 20 cm thick (equal to 15 kg C m^{-2}), which decreases exponentially to 1.2 kg C m^{-2} within 300 years. It is assumed that afforestation accumulates carbon in the growing tree stand biomass until the average value of carbon stock over the forest rotation period is reached. The calculation thus uses the long-term average instead of taking into account the changes that happen in the carbon stock in the trees over the 300 years.

In the chains where the wood biomass or reed canary grass produced in the after-use phase is used for producing energy, the emissions of the production and utilization phases are taken into account. Soil emissions are also taken into account in the case of cultivation of reed canary grass, but there are varying estimates for what their level might be (carbon emissions, carbon sink or carbon-neutral).

The calculations are based on the following assumptions: the energy content of peat per hectare is 9,400 MWh, which corresponds to 3,380 MJ m^{-2}. This gives a peat production area of about 30 ha for one PJ of peat fuel energy. The emissions and sinks of pristine peatlands, production emissions, and the emissions and sinks in the after-use of the peat production area are shown in Table 10. In addition to the average, the minimum and maximum values are given. These are used in sensitivity and uncertainty estimates.

In the calculations for the vision chains (5 and 6) and the peatland utilization chains (C and F), we assume that a new peat production method, the 'biomass drier', will significantly reduce emissions from the production fields and stockpiles. The new harvesting method will enable the production of peat fuel from the entire thickness of the peatland within a short time, shortening the harvesting period from 20 years to one or two years. Our estimate is that emissions from the harvesting area will be very small (counted as zero in the calculations) compared to conventional fuel peat production. The emissions from working machinery and stockpiles are also assumed to be lower (working machinery 0.5 CO_2 MJ^{-1}, stockpiles 0.74 g CO_2 MJ^{-1}) due to more advanced machinery and storage technology. The CH_4 and N_2O emission factors from combustion are estimated to be lower due to the improved combustion technology. The CO_2 emission factor will be lower due to drier peat fuel (moisture content 30% instead of the usual

Table 10. Greenhouse gas (GHG) emissions from coal burning and other coal life cycle phases.

GHG	Combustion emissions (g MJ^{-1})	Other life cycle emissions (g MJ^{-1})	Total (g MJ^{-1})
CO_2	92.19	2.99	95.18
CH_4	0.005	0.335	0.34
N_2O	0.002	0.00	0.002

Peat harvested with a new peat production method on the peat drying field. Solar energy is utilized in the drying process (Photo: Sakari Sarkkola).

45%, resulting in a 3% lower CO_2 emission factor). After-use in the vision chains is afforestation. The amount of residual peat in the cutaway area is very small (assumed to be zero in the calculations), as practically no peat is left for decaying during the afforestation phase. However, the fact that the amount of residual peat is small could cause problems for afforestation, as strong tree growth requires a lot of nitrogen, which is usually obtained from the residual peat. Also, providing suitable drainage for an area where the new peat production method has been used may be problematic.

Coal

The same method was used for estimating the greenhouse impacts of coal and peat to make the results comparable. The greenhouse impact of coal was also studied from the life cycle perspective in the same way as for peat, i.e. by taking into account all the phases in the life cycle from the harvesting to combustion of peat. The information about emissions from the coal production chain is based on the EU ExternE research programme. The information on emissions from combustion is from the pulverized coal boiler at Meri-Pori coal-fired power plant in Finland. The emissions of other phases of the life cycle are assumed to consist mainly of CH_4 emissions from coal mines. These are evaluated on the basis of Polish coal mines. Minor emissions are also caused by the working machinery needed for production and transport. The emissions are shown in Table 10. The greenhouse impact of using Russian coal was also assessed. The greenhouse impacts of Polish and Russian coal are very similar (see Kirkinen et al. 2007).

5.5. Results

The greenhouse impacts of the utilization chains of peat fuel and coal are shown as a function of time in Figure 28. Only the energy use of peat is taken into account in these chains. The considered time span is 300 years. Figure 29 shows that the peat production and combustion are assumed to occur during the first 20 years, during which time the radiative forcing increases strongly. Then the radiative forcing begins to decrease, mainly because of the carbon transfer from atmosphere to oceans (global carbon cycle) and the sequestration of carbon in the growing biomass and litter in the peat production area. If the peat production area is a pristine fen or forestry-drained peatland, there is little difference between the production chains. The peat production chain *pristine fen –*

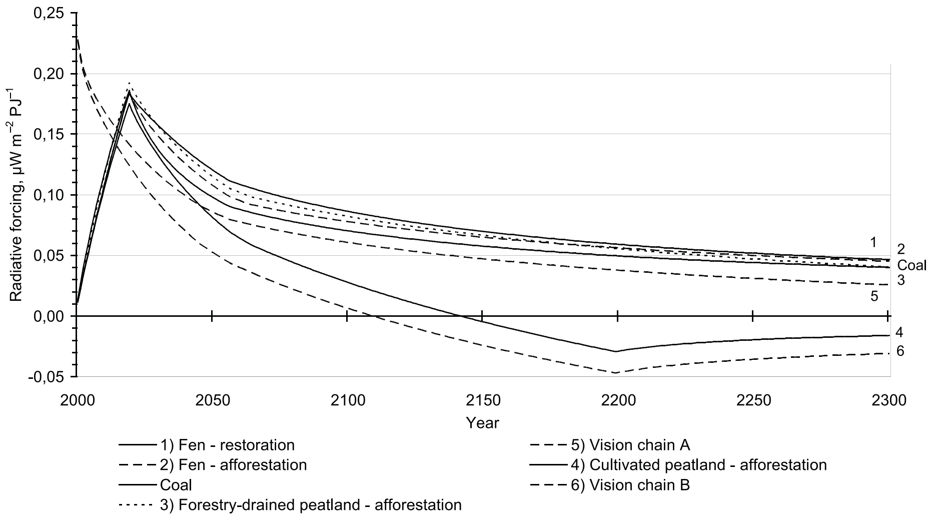


Figure 28. Radiative forcing of different peat production chains and the coal production chains as a function of time. Radiative forcing is presented per global area.

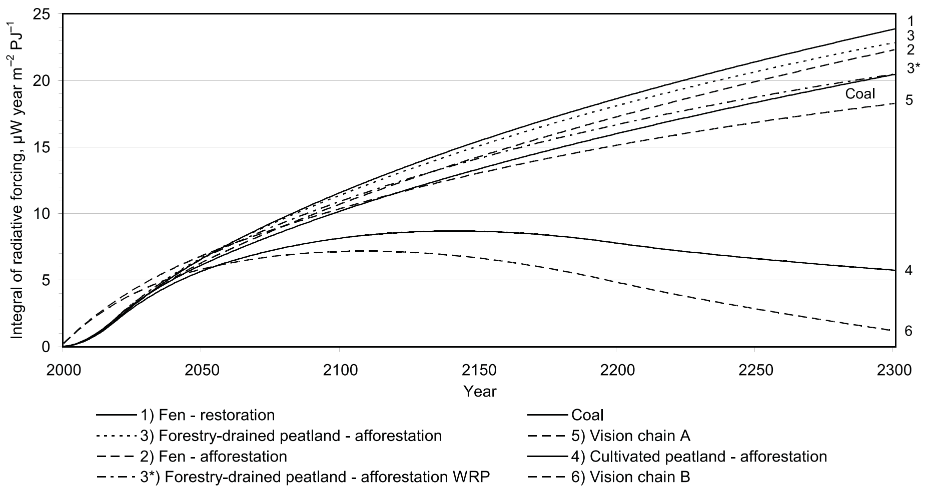


Figure 29. Cumulative radiative forcing of peat and coal utilization chains as a function of time per 1 PJ of energy. The radiative forcing integral is presented per global area. Chain 3* represents a situation where no residual peat is left (without residual peat, WRP).

restoration (1) produces the greatest greenhouse effect, while there is virtually no difference between that of the other chains, such as *pristine fen – afforestation* (2) or *forestry-drained peatland – afforestation* (3). The lowest impact is produced by the chain based on the utilization of organic cropland. This is mainly because the significant emissions from the organic cropland stop when it is taken over for peat harvesting.

The cumulative greenhouse impact of the utilization chains of peat fuel and coal as a function of time over 300 years is shown in Figure 29. This shows the accumulated climate impacts integrated to the value given in the x-axis.

The use of forestry-drained peatland for peat fuel production also causes a slightly greater greenhouse impact than coal, except if the after-use following peat harvesting is afforestation. However, the calculations for this assume that no residual peat is left in the production area (WRP = without residual peat). If the residual peat is harvested as precisely as possible, the greenhouse impact of this chain diminishes to the same level as that of coal.

The most climate-friendly peat utilization chain is *organic cropland – afforestation* (Figure 29). When organic cropland is taken over for peat production, its considerable emissions caused by agricultural use cease, compensating for the emissions from combustion and their transfer to sinks and oceans (cf. carbon cycle) over time because the emissions from the reference state are discontinued. This reduces the greenhouse impact of the utilization of the peat.

Two of the peat utilization chains examined are 'vision chains' (Figure 29). The greenhouse impact of these chains represents the lowest possible greenhouse impact for the use of peat achievable through the minimization of emissions from the various phases of the life cycle through ad-

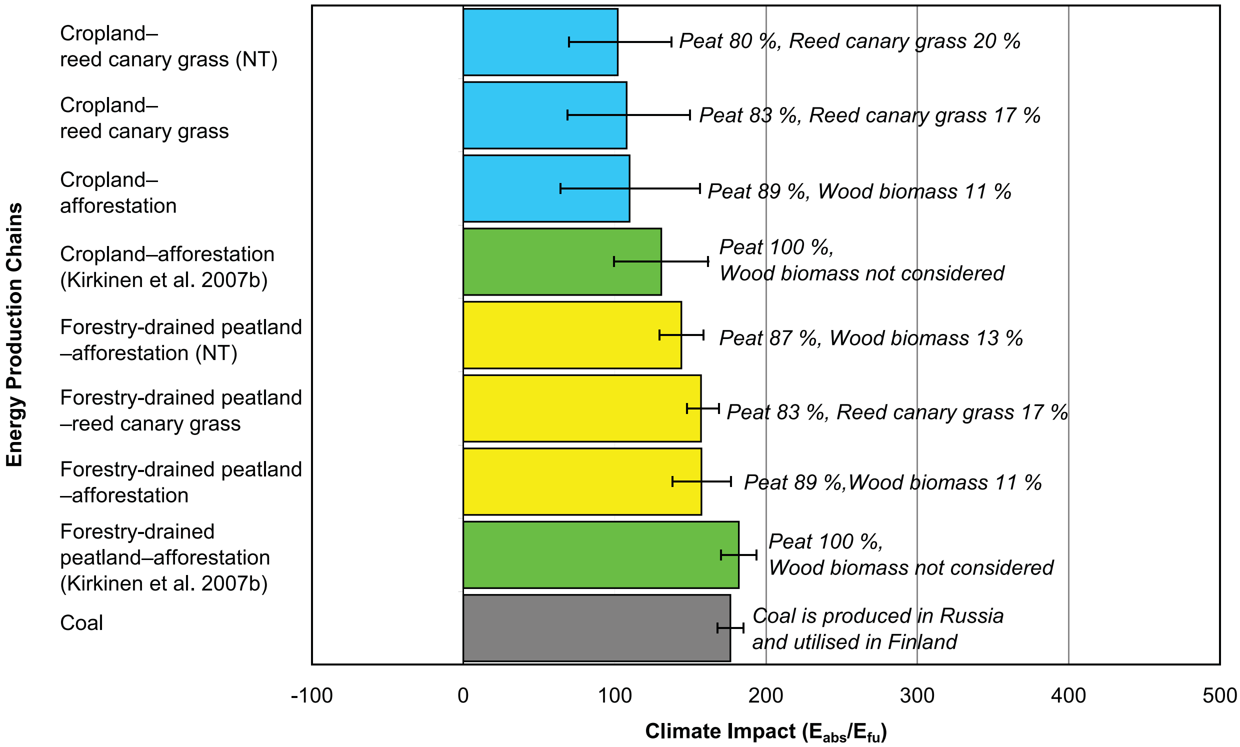


Figure 30. Greenhouse impact of various energy production chains with a time horizon of 100 years, peatland utilization scenario and coal scenario. The bars indicate the greenhouse impact of each chain, while the horizontal lines indicate the uncertainty of the impact. The yellow and blue bars show which portion of the energy produced in the chains is produced using peat and renewable bioenergy, respectively. The greenhouse impact (E_{abs}/E_{fu}) equals the cumulative radiative forcing caused by the emissions and sinks over the life cycle of the chain divided by the energy of the fuel (NT = new peat fuel production technology).

vanced technology and by allocating peat production to areas which currently are major sources of greenhouse gases (organic croplands and forestry-drained peatlands). Advanced technology includes improving combustion technology particularly with regard to N_2O emissions, shorter production times, and technology intended to reduce emissions from the production field and stockpiles (biomass drier). Figure 29 shows that the greenhouse impact of vision chain B, based on organic croplands, begins to decline already in 100 years from the ending of peat production, and almost achieves neutrality in 300 years.

Figures 30 and 31 show the greenhouse impact over 100 and 300 years, respectively, for the peat utilization chains examined, in which the peatland is first used for peat fuel production and then for bioenergy production. If we wish to limit global warming to 2–3 °C, emission reduction measures must be taken in the next few decades. A time horizon of 100 years is thus relevant for studying the greenhouse impacts of fuels.

Figure 30 shows the greenhouse impact of using peat for energy in various chains which in addition to peat combustion include the production of renewable energy (wood biomass or reed canary grass) on the peatland after the peat has been harvested and burned. The time horizon is 100 years. The production reserves are organic cropland and forestry-drained peatland. Renewable energy production helps offset the greenhouse impact from the peat combustion. New production technology also helps reduce the greenhouse impact. For each chain, the figure shows which portion of the overall energy produced in the chain is produced using peat and which using renewable bioenergy. The horizontal lines indicate the uncertainty of the greenhouse impact of each chain.

Figure 31 is similar to Figure 30 showing the greenhouse impact of various peat utilization chains but has a time horizon of 300 years. In the long term, the greenhouse impact of the chains where the production reserve is organic cropland decreases considerably as the area is first used for peat production and then for the production of renewable energy over a long period of time. The lower greenhouse impact compared with the other chains is due to the ceasing of the significant emissions from

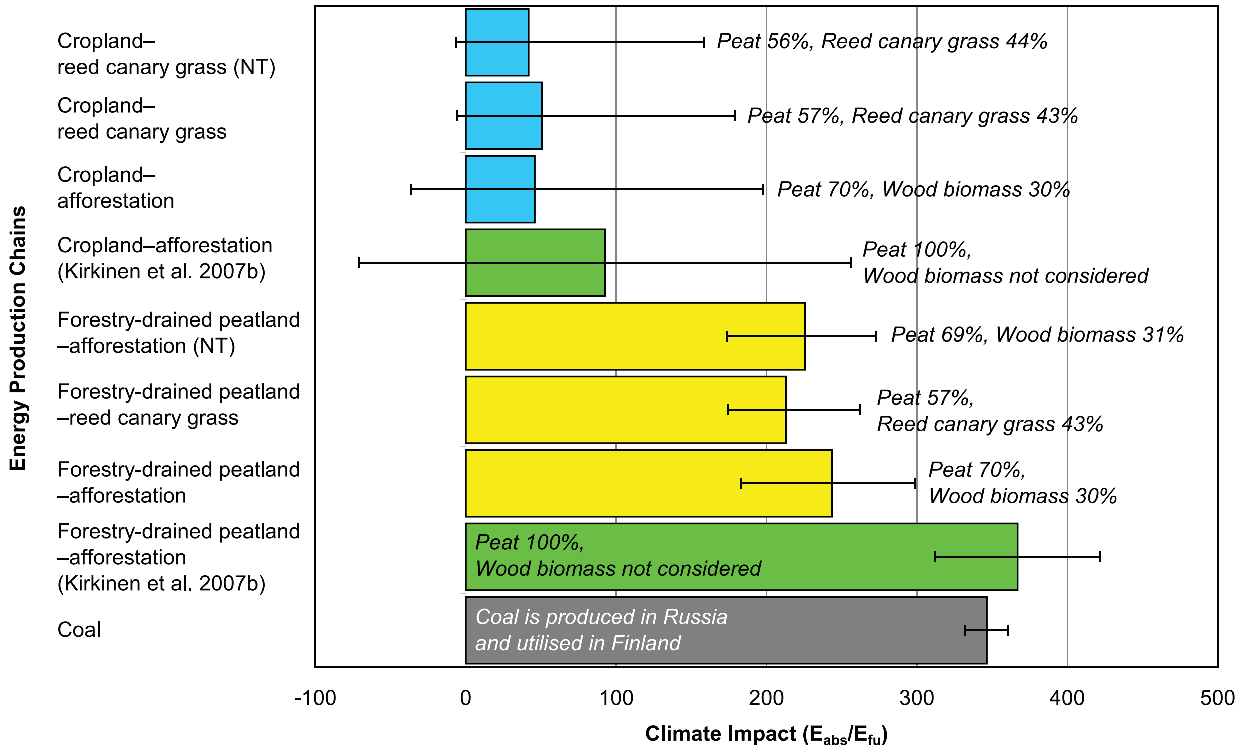


Figure 31. Greenhouse impact of various energy production chains with a time horizon of 300 years. The bars indicate the greenhouse impact of each chain, while the horizontal lines indicate the uncertainty of the impact. The yellow and blue bars show which portion of the energy produced in the chains is produced using peat and renewable bioenergy, respectively. See also the caption for Figure 30.

the organic cropland when it is taken over for peat production.

5.6. Sensitivity analysis

Sensitivity analysis helps identify the factors which contribute the most to the greenhouse impact. Sensitivity analysis is also part of the life cycle analysis. Figure 32 shows the cumulative greenhouse impact of the *forestry-drained peatland – afforestation* peat utilization chain by each phase for the time spans of 100 and 300 years.

Uncertainty varies greatly from one phase of the production chain to another (Figure 32). The most accurate information concerns the emissions from production and combustion in the first 20 years. In the after-use option, the absorption of carbon in the forest is taken into account over the average forest rotation period. In the long term, however, the decomposition of residual peat causes more emissions than the forest can bind carbon, adding to the greenhouse impact; but there is great uncertainty involved here, and the uncertainty increases as the time horizon is lengthened. In particular, there is little information available on the volume of residual peat and its decomposition rate. Taking into account the uncertainty of the greenhouse impact of the afforestation phase, in this case about ± 20%, it is entirely possible that the greenhouse impact of the afforestation phase will be negative.

When peatland is fully utilized for energy production, the greenhouse impact can be divided into components (Figure 33). The time horizon is 100 years. The greenhouse impact at the production phase is mainly caused by peat combustion. The emissions from the energy production and combustion phase are known the best, and therefore the uncertainty here is much less than for the emissions from organic cropland. When organic cropland is taken over for peat production, the ceasing of its natural emissions compensates for some of the greenhouse impact of the utilization of the peatland for fuel.

The emission data for the life cycle phases of peat fuel utilization are given in the following table (Table 11). Positive figures indicate emission (source), and negative figures indicate accumulation (sink). The emissions from the use of the wood biomass or reed canary grass after the after-use of the production area are taken into account. For a more detailed discussion of these emissions and sinks, see Kirkinen et al. (2007).

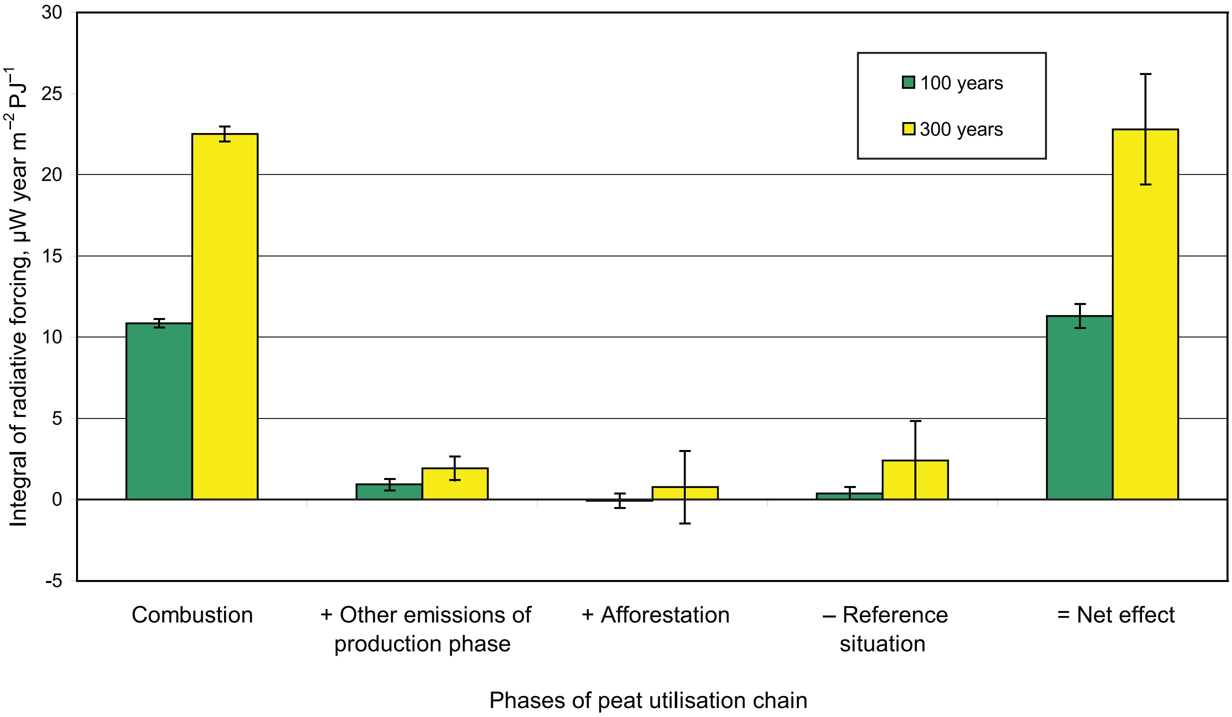


Figure 32. The cumulative greenhouse impact for the *forestry-drained peatland – afforestation* peat utilization chain by each phase of life cycle calculated for 100 and 300 years, per 1 PJ of energy. The net effect is calculated by subtracting the greenhouse impact of the reference chain from the greenhouse impact caused by the combustion, other production emissions and afforestation emissions/sinks in the chain examined. The vertical lines indicate uncertainty due to input data variation (see input values, Table 10).

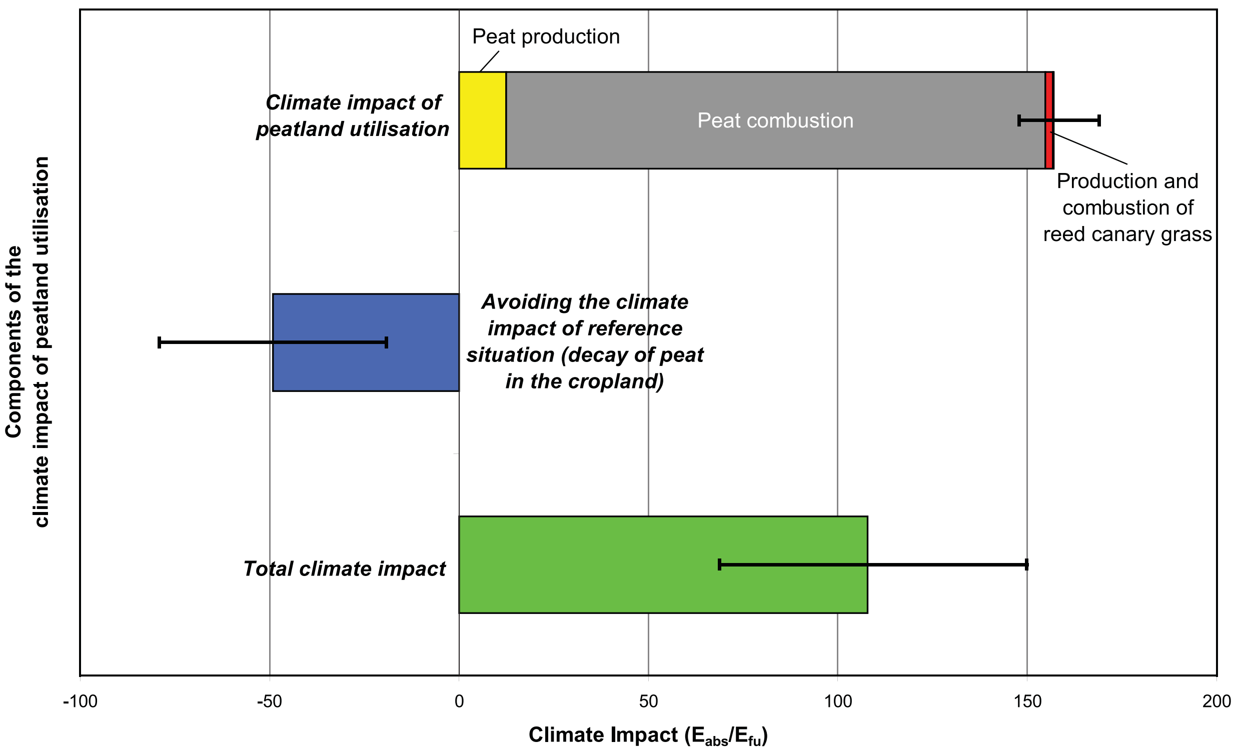


Figure 33. Analysis of the climate impact of the *cultivated-peatland – reed canary grass* utilization chain into components over a time horizon of 100 years. The impact is analysed into energy production and combustion emissions, the avoided emissions of the reference state (organic cropland) and the combined greenhouse impact. The Figure shows the chain with scenario A (which does not include CO_2 sequestration or emissions into the soil of the reed canary grass cultivation area). See also the caption for Figure 30.

Table 11. GHG emissions and sinks over the life cycle of peat fuel. Positive figures indicate net flux into the atmosphere and negative figures indicate net influx from the atmosphere.

Production reserve	Average	Min	Max	Source
Pristine fen				
CO_2, g m^{-2} a^{-1}	–73.34	0	–146.68	Saarnio et al. 2007
CH_4, g m^{-2} a^{-1}	22.66	14.66	30.66	Martikainen et al. 1993
N_2O, g m^{-2} a^{-1}	0	0	0	
Forestry-drained peatland				
[1] CO_2, g m^{-2} a^{-1}	224	–214	420	Minkkinen et al. 2006
CH_4, g m^{-2} a^{-1}	0	0	0	Minkkinen et al. 2007b
N_2O, g m^{-2} a^{-1}	0	0	0	Penttilä et al. 2007
Organic cropland				
CO_2, g m^{-2} a^{-1}	1,760	705	2,815	Maljanen et al. 2007
CH_4, g m^{-2} a^{-1}	–0.147	–0.263	–0.031	Maljanen et al. 2007
N_2O, g m^{-2} a^{-1}	1.297	0.462	2.132	Maljanen et al. 2007
Peat utilization				
Peat production area				
CO_2, g MJ^{-1}	6.84	3.42	10.25	Alm et al. 2006
CH_4, g MJ^{-1}	0.0039	0.0019	0.0058	Tilastokeskus 2005b
Stockpiles				
CO_2, g MJ^{-1}	1.48	0.74	2.23	Nykänen et al. 1996
Working machinery				
CO_2, g MJ^{-1}	1	0.5	1.5	Uppenberg et al. 2001
Combustion				
CO_2, g MJ^{-1}	105.9	105.3	106.5	Vesterinen 2003
CH_4, g MJ^{-1}	0.0085	0.0064	0.0106	Tilastokeskus 2005
N_2O, g MJ^{-1}	0.0128	0.0032	0.0224	Tilastokeskus 2005
After-use of peat production area				
Afforestation				
Carbon sequestration in growing biomass [2] (CO_2, g m^{-2} a^{-1})	–448	–359	–505	Penttilä et al. (unpublished)
Accumulation of above-ground litter [3] (CO_2, g m^{-2} a^{-1})	–147	–122	–155	Penttilä et al. (unpublished)
Accumulation of below-ground litter (CO_2, g m^{-2} a^{-1})	–15	0	–22	Penttilä et al. (unpublished)
Restoration				
CO_2, g m^{-2} a^{-1}	–121.6	27.9	–271.0	Alm et al. 2007
CH_4, g m^{-2} a^{-1}	22.66	14.66	30.66	Alm et al. 2007
N_2O, g m^{-2} a^{-1}	0	0	0	Alm et al. 2007

[1] Only includes changes of carbon in the soil, not changes in the carbon in the biomass (trees, surface vegetation).
[2] The trees absorb carbon until the average carbon stock for the forest rotation period is achieved (5.5 kg C m^{-2}).
[3] Forest litter absorbs carbon until the carbon stock is achieved (1.8 kg C m^{-2}).

5.7. Discussion

Examining greenhouse impact from the life cycle perspective is an approach different from the greenhouse gas inventory. The life cycle perspective aims at estimating all the effects of a function (or product), including all the significant emissions and sinks caused by the function (or product). In the case of a conventional product, all emissions occur within a few months or at most within a few years. The emissions occurring in different years are added up, and no particular attention is paid to the time span. In the case of peat fuel, however, the restoration or afforestation of cutaway peatland may cause emission and sink processes lasting up to hundreds of years, and therefore it makes sense to introduce a time dimension to the study and to the way in which the results are presented. Since the study involves potential emissions and sinks far in the future, its results are not compatible with the inventory approach, which only takes into account the emissions and sinks of the report year. Also, the greenhouse gas inventory reports emissions by sector and by emission class, and the life cycle emissions of a single function, such as the use of peat for energy, are split up among several emissions classes (e.g. combustion, harvesting machinery and after-use of the peat production area).

Selecting a suitable time horizon for the life cycle analysis of peat fuel is problematic. Peat renews very slowly, over millennia. A forest, by contrast, grows to its full height in less than a century. CO_2 released into the atmosphere is slowly absorbed by the oceans, over one or even several centuries. On the other hand, if the aim is to halt the rise in the levels of greenhouses in the atmosphere, as is the aim of the UNFCCC, greenhouse gas emissions worldwide must be cut to less than half of their present level. If the aim is to limit global warming to an increase of 2 °C in the average temperature of the Earth, as the European Union has proposed, greenhouse gas emissions worldwide must be cut to half of their present level within about 50 years. The usual approach is to use the Global Warming Potential (GWP) factors for the various greenhouse gases over a period of 100 years. This is the case in the National Greenhouse Gas Inventory under the UNFCCC.

In the present study, cumulative greenhouse impacts have been considered over a period of 300 years. It must be noted that such long-term studies involve much uncertainty due to future climate changes or land use changes.

The sensitivity analysis aimed to reflect the effect of uncertainty or variation in the input values reflecting emissions and sinks on the results. The results were also affected by the models used to calculate concentrations and radiative forcing. However, as the same models were used for all peat utilization chains and the coal utilization chain in this study, the relative differences in the results for the various chains reflecting differences in the input values are justifiable. The models were drawn up so as to conform to the estimates used in the Third Assessment Report of the IPCC (2001).

5.8. Conclusions

- According to the results of the study, the most climate-favourable peat energy production chain is based on the use of peat from peatlands in agricultural use.

- Taking only peat into account, the use of peat energy chains based on the use of peat reserves on forestry-drained peatlands and on pristine sedge-fens causes roughly the same greenhouse impact per energy unit produced as the use of coal. If forestry-drained peatland is first used for peat fuel production and then for the production of renewable bioenergy in the long term, the greenhouse impact is lower than that of coal. Producing renewable bioenergy at such sites after peat harvesting is discontinued decreases the overall greenhouse impact per energy unit produced.

- Afforestation is a slightly more climate-friendly form of after-use than restoration for cutaway peatland, at least in a 300-year time horizon. Cultivation of reed canary grass is roughly equal to afforestation in terms of its greenhouse impact.

- Harvesting all residual peat, improving combustion technology and employing new peat fuel production methods will clearly reduce the greenhouse impact of peat. By improving production and combustion technologies, the greenhouse impact of peat is reduced so much that peat becomes more climate-friendly than coal in the long term.

- The sensitivity studies conducted in the research project show that the greenhouse impact of peat combustion is fairly accurately known. However, because the utilization chains examined extend far into the future, there is a wide margin of uncertainty in the results. The results are only accurate as regards emissions from peat harvesting and combustion, occurring in the next 20 years. The greatest uncertainty is in the emissions and sinks data for the peat production area (production reserve) and forms of after-use. Emissions and sinks are here assumed to be known for the next 100 or 300 years. No allowance is made for future climate change or land use changes, which nevertheless are highly likely over such a long time period.

6. Final conclusions of the research programme

- The research programme contributed substantially to the knowledge about the impact of land use on the greenhouse gas balance of Finland's peatlands, and in some respects the prevailing conceptions about greenhouse gas emissions were significantly revised.
  - The carbon dioxide balance of forestry-drained peatland used to be considered positive, but the new findings show that, on average, it is negative (forestry- drained peatland looses carbon).
  - By contrast, the current data on substantial emissions of carbon dioxide and nitrous oxide from current or former organic cropland were confirmed by the new findings.
  - It was somewhat surprising to note that afforestation of organic cropland is not enough to render the overall greenhouse gas balance positive, although it does reduce emissions.

- The purpose of the greenhouse gas inventory under the UNFCCC is to report as accurately as possible the actual anthropogenic greenhouse gas emissions and sinks during the report year. This enables, inter alia, monitoring the true development of greenhouse gases and assessment of meeting the commitments under the Kyoto Protocol.

- Life cycle assessment of greenhouse impacts differs from the greenhouse gas inventory in that it takes into account all the significant emissions and sinks caused by the product in question. The present research programme concerned the greenhouse impacts of the use of peat for energy from the life cycle assessment perspective.

- With present methods, the use of peat for energy causes a greenhouse impact of similar magnitude as the use of coal. The results, however, include uncertainty partly due to the long integration periods considered, and partly due to the unknown distribution of initial state emissions of the formerly forestry-drained peatlands, currently under peat production. Taking into account the use of peatland for renewable bioenergy production after peat harvesting is finished, the greenhouse impact of the overall energy use of peatland is less than that of coal.

- The greenhouse impact of peat can further be significantly reduced by directing peat harvesting to current or former organic cropland and to those forestry-drained areas which have high emissions in their current state. In these cases, the greenhouse impact decreases significantly in the long term.

- The greenhouse impact of peat energy can be decreased by thorough utilization of residual peat, improvement of combustion techniques, and with new peat harvesting methods. The production of renewable bioenergy in the areas available after peat harvesting will decrease the greenhouse impact per total produced energy unit. Afforestation is slightly more climate-friendly as an after-use measure for cutaway peatland than restoration. Cultivation of reed canary grass has roughly the same effect as afforestation with regard to the greenhouse impact.

- Peatland restoration aims at removing human impact and restoring the natural condition. Indeed, there is a case for considering restoration as a temporary form of land use for returning an area to the state in which it was before human intervention. Accordingly, restored peatlands could be removed from greenhouse gas inventories, corresponding to pristine peatlands, after a certain time period.

- Knowledge on the greenhouse impact of land use in peatlands is still fragmented and largely deficient. More research is needed particularly on the net exchange of carbon dioxide (soil carbon balance) of forested peatlands in different peatland site types from the southern and northern parts of Finland and on nitrous oxide balances on nutrient-rich peatlands, especially organic croplands. The knowledge on greenhouse gas balances of cut-away peatlands after peat harvesting and from the different after-use options is still meagre, since there are only few such areas at present. The proportion of these areas will increase considerably in the future, however, and more research should be conducted.

Scientific articles published under the research programme

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APPENDIX

Greenhouse Impact of the Use of Peat and Peatlands in Finland

– Research programme component projects and their researchers

UH = University of Helsinki; UJ = University of Joensuu; UKU = University of Kuopio
FMI = Finnish Meteorological Institute; GTK = Geological Survey of Finland;
VTT = VTT Technical Research Centre of Finland

Coordination project
Jukka Laine (Metla), Kari Minkkinen (UH), Jukka Alm (Metla)

Model development and regional calculations
Jukka Alm (Metla), N.J. Shurpali (Metla), Sanna Saarnio (UJ), Micaela Morero (UJ), Prof. Jukka Laine (Metla), Högne Jungner (UH), Kari Minkkinen (UH), Markku Mäkilä (GTK), Eeva-Stiina Tuittila (UH), Harri Vasander (UH)

Measurement quality system
Kari Minkkinen (UH), Jouni Meronen (UH)

Net CO_2 flux on forested peatlands
Tuomas Laurila (FMI), Annalea Lohila (FMI), Mika Aurela (UJ), Tea Thum, Jukka Laine (Metla), Lasse Aro (Metla), Kari Minkkinen (UH), Timo Penttilä (Metla), Juha-Pekka Tuovinen (FMI), Terhi Riutta (UH), Janne Rinne (UH), Mari Pihlatie (UH), Timo Vesala (UH)

Greenhouse gas balances in pristine peatlands
Sanna Saarnio (UJ), Micaela Morero (UJ), Docent Jukka Alm (Metla Joensuu), Högne Jungner (UH, dating laboratory), Prof. Jukka Laine (Metla), Markku Mäkilä (GTK), Eloni Sonninen (UH, dating laboratory), Eeva-Stina Tuittila (UH), Docent Harri Vasander (UH)

Greenhouse gas balances in forestry-drained peatlands
Kari Minkkinen (UH), Jukka Laine (Metla), Raija Laiho (UH), Päivi Mäkiranta (Metla), Timo Penttilä (Metla), Marjut Karsisto (Metla), Risto Sievänen (Metla), Mike Starr (Metla), Veikko Kitunen (Metla), Teija Dahlin (Metla Rovaniemi), Mauri Heikkinen (Metla Rovaniemi), Timo Törmänen (Metla Rovaniemi).

GHG balances in afforested organic croplands and cutaway peatlands
Jyrki Hytönen (Metla), Lasse Aro (Metla), Jukka Laine (Metla), Marja Maljanen (UKU), Docent Jukka Alm (UJ), Päivi Mäkiranta (Metla), Pertti J. Martikainen (UKU), Hannamaria Potila (Metla), Kari Minkkinen (UH), Mari Pihlatie (UH), Narasinha Shurpali (UJ)

GHG emissions from cultivated and abandoned organic soil croplands
Pertti Martikainen (UKU), Marja Maljanen (UKU), Hannu Nykänen (UKU), Jyrki Hytönen (Metla), Martti Esala (MTT), Jyrki Hytönen (Metla), Päivi Mäkiranta (Metla), Jukka Alm (UJ), Kari Minkkinen (UH), Jukka Laine (Metla)

Restoration of cutaway peatlands
Eeva-Stiina Tuittila (UH), Jukka Laine (Metla), Harri Vasander (UH), Kari Minkkinen (UH), Kari Kukko-Oja (Metla), Jukka Alm (Metla), Sanna Saarnio (UJ), Mirva Leppälä (Metla), Mika Yli-Petäys (UH), Sanna Kivimäki (UH)

Radiative forcing and life cycle analysis models
Ilkka Savolainen (VTT), Riitta Korhonen (VTT), Johanna Kirkinen (VTT)

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