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Excavation-drier method of energy-peat extraction reduces long-term climatic impact

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Climatic impacts of energy-peat extraction are of increasing concern due to EU emissions trading requirements. A new excavation-drier peat extraction method has been developed to reduce the climatic impact and increase the efficiency of peat extraction. To quantify and compare the soil GHG fluxes of the excavation drier and the traditional milling methods, as well as the areas from which the energy peat is planned to be extracted in the future (extraction reserve area types), soil CO_2, CH_4 and N_2O fluxes were measured during 2006–2007 at three sites in Finland. Within each site, fluxes were measured from drained extraction reserve areas, extraction fields and stockpiles of both methods and additionally from the biomass driers of the excavation-drier method. The Life Cycle Assessment (LCA), described at a principal level in ISO Standards 14040:2006 and 14044:2006, was used to assess the long-term (100 years) climatic impact from peatland utilisation with respect to land use and energy production chains where utilisation of coal was replaced with peat. Coal was used as a reference since in many cases peat and coal can replace each other in same power plants. According to this study, the peat extraction method used was of lesser significance than the extraction reserve area type in regards to the climatic impact. However, the excavation-drier method seems to cause a slightly reduced climatic impact as compared with the prevailing milling method.

Introduction

Peat is currently an important domestic fuel in Finland. The share of peat fuel was ca. 7% of the total primary energy use in 2008 (Energiateollisuus 2009). On the other hand, global warming issues related to the utilisation of peat remain an important subject of public debate. Peat combustion produces large amounts of carbon dioxide (CO_2) (Vesterinen 2003), the most important GHG, which is emitted also in other phases of the energy-peat extraction chain (Ahlholm & Silvola 1990, Nykänen *et al*. 1996, Cleary *et al*. 2005, Alm *et al*. 2007a, Kirkinen *et al*. 2007, 2010). Additionally, peat extraction releases other GHGs, such as methane (CH_4) and nitrous oxide (N_2O) (Alm *et al*. 2007a, Kirkinen *et al*. 2007, 2010). Thus, according to the earlier

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studies, the GHG emissions during energy-peat extraction from fields and stockpiles can be remarkable (Savolainen *et al*. 1994a, Savolainen *et al*. 1994b, Uppenberg *et al*. 2001, Nilsson and Nilsson 2004, Alm *et al*. 2007a). However, there is some indication that the long-term GHG emissions can be reduced with the appropriate choice of extraction method (Nilsson and Nilsson 2004, Holmgren *et al*. 2006, Kirkinen *et al*. 2007, 2010).

To reduce the climatic impact and to increase the efficiency of peat extraction, a Finnish peat mining company Vapo Ltd. has started the development of a new peat-extraction method. Because achieved energy-peat yield in this excavation-drier method may be as high as 20-fold as compared with that of the traditional milling method (500 MWh ha^{-1} y^{-1} and 10 000 MWh ha^{-1} y^{-1}, respectively), it is not necessary to simultaneously open large areas for peat extraction. Thus, environmental effects, including GHG emissions, may be smaller.

The excavation-drier method enables energy-peat extraction in smaller areas which are difficult to utilize with the milling method. Thus, it is easier to direct extraction to areas with high GHG emissions in their current state, such as abandoned organic croplands. This study aims to assess the potential of technical solutions and selection of extraction sites for reduction of GHG emissions from energy-peat extraction. We studied the GHG emissions from both the excavation-drier method and the milling method, and compared the long-term (100 yr) climatic impacts of these methods modelled for three different peat extraction reserve areas.

The most established and well developed method to evaluate environmental impacts of products or services for decision making is the life cycle assessment (LCA) (Ness *et al*. 2007). LCA focuses on the physical chain of material and energy flows related to products and services. The results of inventory analysis related to life cycle are combined into different impact categories according to their environmental impacts (EN ISO 14044:2006).

Data sources in LCA differ from those used in more traditional modelling methods. The data used in LCA can be based on measurements or alternatively they can also be produced by calculations or based on estimates or information from literature (EN ISO 14044:2006). In traditional static modelling methods, the relationships between inputs and outputs are created based on physical laws, but in the case of LCA modelling this is not viable. Therefore, to analyse the uncertainties from the aspect of results, sensitivity analyses are needed in a LCA study (EN ISO 14044:2006).

The time frame and the depth of the study have to be decided depending on the goal and scope of the study (ISO 14040:2006). It is important to take into account all the environmental impacts throughout the life cycle. When the purpose is to determine the environmental impacts of harvesting a drained peatland, the inclusion of the land use before, during and after the extraction is justified. Furthermore, when peat is utilised in energy production, the emissions produced with the replaced fuel can be included in the avoided emissions.

In this study, the Life Cycle Assessment (LCA), described at a principal level in the ISO Standards 14040:2006 and 14044:2006, was used to assess the greenhouse impact of peatland utilisation with respect to land use and peat production chains. It is assumed that the increase in the utilisation of peat decreases the use of coal in the studied system in proportion to the energy content of the fuel, and consequently replaces the emissions from coal combustion. The fuel type identified as being substituted or used for production of the substituted energy may have significant impacts on the overall result of the assessment (Fruergaard *et al*. 2009). The marginal data present in the short-term an existing technology which is capable to respond to a change in demand by adjusting its output (Weidema *et al*. 1999, Fruergaard *et al*. 2009). In the deregulated Nordic power market, coal condensing power represents marginal production (Johansson *et al*. 2006, Thyholt & Hestnes 2008).

The main focus was on the emissions before (production reserve) and during harvesting because it was the life cycle stage with the most complete data. The calculations for area specific GHG emissions were done by using measurement data from Isosuo, Aitoneva and Kortessuo. The values that represent the average

forestry drained peatland emission data (Alm *et al*. 2007a, Minkkinen *et al*. 2007a, Kirkinen *et al*. 2010) were also included in the study.

Material and methods

Excavation-drier method *vs.* milling method

In the excavation-drier method, peat is extracted with an excavator, transported to a separate peat drying field (biomass drier) with a high power pump, spread onto the biomass drier with a special tractor-pulled spreader cart and finally collected with a traditional collector cart (Savolainen and Silpola 2008). Vegetation cover can be kept intact in the peat extraction area until the harvesting starts, and there is no need for effective drainage of the extraction field. Less than 1 ha area may be opened annually for a single extraction field (Savolainen and Silpola 2008).

The biomass drier can be either an asphalted or an effectively subsurface-drained, peat covered 3–10 ha field. The drying process of extracted peat is much more rapid on the separate biomass-drier than on the conventional milling-method field. In optimal weather conditions, the drying process lasts 24–36 hours as compared with the drying time of ca. one week in the conventional method (Savolainen and Silpola 2008). Thus, the weather risks of peat extraction are also reduced. The end product of the excavation-drier method is small-sized sod peat. The diameter of sod-peat pieces is 1–4 cm, depending on the spreader technology (Savolainen and Silpola 2008).

For comparison, when applying the conventional, prevailing milling method, the peat extraction field is effectively drained and all vegetation is removed prior to extracting (Savolainen and Silpola 2008). Nowadays in Finland, ca. 85% of the extracted peat, both energy and horticultural peat, is produced by the milling method (Savolainen and Silpola 2008). A thin granular layer of fine peat "dust" is milled at a time, which is then dried on the surface of the field to a moisture content of ca. 40%. Dry peat is then ridged on the middle of the strip before actual collection. The minimum area of an extraction field is currently ca. 20 ha. A single harvesting chain is able to utilise a extraction area 300–700 ha in size.

Study sites

Since 2004, six peat-extraction areas using the excavation-drier method have been established in different parts of Finland for research purposes. Extraction operations using the reference milling method and the excavation-drier method were commenced simultaneously near each other. GHG emissions were studied during 2006–2007 in three of the excavation-drier method's extraction areas: Isosuo (61°04´N, 23°02´E), Aitoneva (62°12´N, 23°17´E) and Kortessuo (65°14´N, 26°38´E). The study sites were located in regionally important peat-extraction areas in Finland, and they represented different climatic conditions (Table 1).

The Isosuo site was an abandoned, vegetationless milled peat extraction area that was used as a temporary storage area. Its peat layer was ca. 1.5 m thick and consisted of rather well-humified *Sphagnum–Carex* peat (H 5–6 according to the scale of von Post; Puustjärvi 1970). The Aitoneva site was an abandoned sod-peat storage area. Pine tree stand of ca. 80 m^3 ha^{-1} existed on the site on the site before clearing for extraction. Peat layer was up to 4.5 m thick and consisted of well–humified *Carex* peat (H 7–9). The Kortessuo site had been drained for forestry in the 1970s, and it was used as a temporary road and storage area. Peat layer in Kortessuo was ca. 1.5 m thick and consisted of rather well-humified *Carex* peat (H 6–7). These extraction reserve sites were used as references for the extraction fields, and all of the extraction reserves can be considered as edge areas of peat extraction fields.

Measurements and analyses

The GHGs investigated in this study were carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Aluminium collars (0.07 m^{-2}) with a 25 cm long sleeve were inserted into the soil in 2005 prior to GHG measurements. Where

the milling method was applied, collars were inserted into the soil only temporarily because of continuous peat extraction in the fields. In this study, GHG measurements were done only when the loose, well-aerated milled layer was removed and the solid soil surface was revealed. The GHG data collected from Aitoneva during the summer of 2005 was excluded from the data set because of different measuring methods used, i.e., measurements were also made from recently-milled peat surfaces (Alm *et al*. 2007a). Furthermore, the remaining peat layer in some of these fields in Aitoneva was so thin that there was some mineral soil admixture in the peat. The loose, well-aerated milled layer with a mineral soil admixture was associated with abnormally high CO_2 effluxes (Alm *et al*. 2007a). The GHG measurements were made from stockpiles not covered by plastic foils, and thus should not exaggerate the emissions due to channeling of the gas flows by an impermeable plastic foil layer.

CO_2 effluxes (soil respiration) were measured using the closed-chamber method, which employs a portable infrared CO_2-analyzer (EGM-4, PP-Systems Inc.) over a measurement period of ca. 80 seconds (Alm *et al*. 2007b, Minkkinen *et al*. 2007a). CO_2 effluxes were calculated automatically by the built-in EGM program, but all measurements were checked and corrected afterwards if some anomalies were observed. CH_4 and N_2O fluxes were measured by means of the static closed chamber method, in which a series of air samples is taken *in situ* into four syringes from the headspace of the chamber during a measurement period of 35 minutes (Alm *et al*. 2007b, Minkkinen *et al*. 2007b). CH_4/N_2O concentrations in the samples were analyzed with a gas chromatograph within 24 hours after sampling. The existing vegetation was removed prior to CO_2 efflux measurements. Thus, only soil heterotrophic respiration without autotrophic vegetation respiration was measured. CH_4/N_2O fluxes were measured from separate plots with existing vegetation.

CH_4/N_2O fluxes were calculated from the linear change in CH_4/N_2O concentration inside the chamber as a function of time. Simultaneously with gas sampling, temperatures (5–20 cm from soil surface) in peat profiles were measured. Continuous weather data (air and soil temperatures, precipitation and PAR) were collected by automatic weather stations at the study sites. The depth of 5 cm was chosen for the driving variable in CO_2 efflux model building since it was found to be the best single depth for predicting CO_2 effluxes.

Prior to statistical analyses normality of the GHG data was tested with Shapiro-Wilk's test. Since the CO_2-efflux data were normally distributed, one-way ANOVA with post-hoc test (Tukey HSD) was used for the analysis of the CO_2-efflux differences. Since the CH_4 and N_2O data were not normally distributed, a non-par-

Table 1. Climatic characteristics in the study sites during the measurement years and the period 1971–2000. T_{air} is air temperature (°C) 2 m above ground and T_5 soil temperature (°C) 5 cm below ground.

	Mean T_{air}		T_{air} sum (dd. > 5 °C)	Precipitation (mm)		Mean annual T_5
	annual	aummer		year	winter	
Isosuo (61°04´N, 23°02´E)						
1971–2000	4.5	14.9	1259	593	108	
2006	5.8	17.0	1629	627	79	6.9
2007	7.3	16.1	1432	696	192	6.3
Aitoneva (62°12´N, 23°17'E)						
1971–2000	3.1	13.9	1081	653	126	
2006	4.8	16.4	1485	689	62	6.2
2007	4.4	15.0	1212	717	228	5.6
Kortessuo (65°14´N, 26°38´E)						
1971–2000	2.4	14.5	1105	523	100	
2006	3.4	16.0	1374	442	73	6.7
2007	3.5	14.9	1142	634	144	4.6

ametric Kruskall-Wallis test was used for the analyses of both CH_4- and N_2O-flux differences. Relationships between GHG fluxes and soil factors were analysed using Pearson's correlation analysis. All calculations were carried out using SPSS 17.0 (SPSS Inc.).

At all study sites, the estimated annual GHG flux was based on several individual measurements in space and time during both summer and winter over 2 years. CO_2 effluxes are closely dependent on soil temperature. Thus, to simulate seasonal (May–October) CO_2 effluxes in peat extraction areas excluding stockpiles and biomass driers, we used hourly soil temperature (5 cm below soil surface, T_5) as a driving variable to build site-specific exponential regression models (CO_2 efflux = $ae^{b \times T_5}$). Average CO_2 effluxes for winter (November–April) were integrated from the measurements. For stockpiles, soil T_5 is not the determining factor in CO_2 effluxes, but rather the volume of the stockpile that is normally largest in winter. Temperatures on asphalted biomass driers vary considerably and rapidly depending on direct sunshine and air temperature. In addition, CO_2 effluxes from biomass driers depend largely on peat moisture content. Thus, to estimate both summer and winter CO_2 effluxes from stockpiles and biomass driers we use averaged values of measured fluxes. The summer, winter and annual CH_4 and N_2O fluxes derived from several individual measurements in space and time were averaged. The peat type, degree of decomposition, pH, C and N concentrations of the peat were determined once during the study period from average soil samples down to 20 cm from soil surface.

Analyses of the long-term climatic impact

It is already known that the burning of peat produces more CO_2 than the burning of coal (Vesterinen 2003). However, GHG are also emitted by forestry-drained peatlands even if nothing is done. Therefore, when considering different land-use options it is essential that GHG emission reductions from forestry-drained peatlands are also taken into account. To determine the soundness of peat utilisation in practice, different alternatives for managing drained peatlands have to be compared against the reference scenario in which nothing is done. This LCA approach answers the question, what the change in the climatic impact over a 100 year time span is, if peat is extracted from drained peatlands and utilised for the production of energy as compared with a non-utilisation scenario in which energy is produced from coal.

This study compares different scenarios by setting the system boundary according to a system expansion approach using a case study, which deals with peatland utilisation and peat fuel production from drained peatlands (Fig. 1). To compare the GHG net impact of different utilisation options, 16 scenarios for the calculation procedure were created. The GHG emissions caused by peatland utilisation (E_U) were compared with emissions caused by the non-utilisation scenario (E_L, present state) and fossil fuel utilisation scenario (E_F) which together form the reference scenario (E_R) during the same period (100 years). The differences in the GHG impacts of various peatland utilisation scenarios are due to original emissions of forestry-drained peatland area, peat extraction fields and peat extraction method. The present state of a drained peatland was considered the reference state and thus serves as the basis for calculating the emissions. The results from other scenarios are presented in comparison with the reference state. The fossil fuel utilisation scenarios include emissions from coal utilisation corresponding to the peat-based fuel production. Reference fossil fuel utilisation (E_R) scenarios produce an equal amount of energy as the peatland utilisation (E_U) scenario measured as the energy content of the utilised fuel.

$$E_{net} = E_U - E_R \quad (1)$$

The drained peatland utilisation scenario includes the emissions/uptakes caused by the preparing of the area for peat cutting, peat collecting, the emissions from storage, transportation and burning of peat fuel, as well as the emissions/uptakes from the after-treated area. The uptake by after-treatment area includes afforestation where long-time average carbon stock is considered in scenarios in which wood biomass

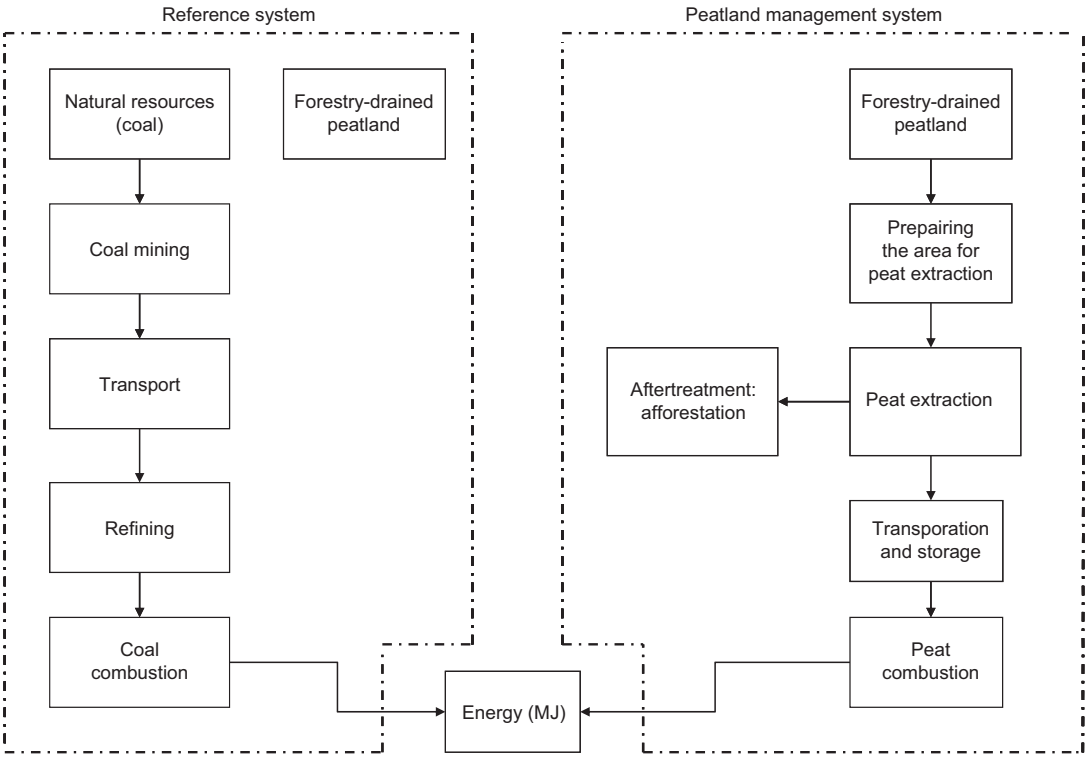

Fig. 1. Compared scenarios. Combustion efficiencies are assumed to be the same for peat and coal.

is not utilised for energy purposes. The total GHG emissions due to peat utilisation scenario are the following:

$$E_U = E_H + E_C + E_A \quad (2)$$

where E_H are the emissions caused by peat extracting and denotes the emissions caused by peat collecting and stockpiling, E_C are the emissions caused by combustion of peat and biomass-derived fuels, and E_A are the emissions caused by the after treatment at the peat production site. The GHG implications of the reference scenario can be summarised as:

$$E_R = E_L + E_F \quad (3)$$

The scenarios were created to compare different chains which consist of different peatland emission baselines, harvesting methods (excavation/milling), after-treatment (afforestation/restoration) and peat utilisation for fuel use (combustion). For this study, the additional GHG-emission data were obtained from various sources, such as the peat industry (www.turveruukki.fi), and the ongoing and previous studies (Nykänen *et al*. 1996, Pingoud *et al*. 1997, Vesterinen 2003, Mäkinen 2006, Alm *et al*. 2007, 2007b, Kirkinen *et al*. 2007, Minkkinen *et al*. 2007b, Silvan 2007, J. Alkkiomäki pers. comm.). The data were utilised to generate estimates of potential GHG-emission reductions per unit of land area in CO_2 equivalents (CO_2e ha^{-1}) of utilised drained peatland area. A one ha area of drained peatland was used as the functional unit in order to make straightforward comparisons between scenarios. The system boundary covers the peat production from field preparation to after treatment and peat combustion. For fossil fuel, the system boundary extended from extraction to utilisation. The GHG emissions from ash disposal are assumed to be negligible in both fuel chains.

Results

Measured GHG fluxes

CO_2 effluxes were significantly lower at all sites after peat extraction with both methods as compared with those of the extraction reserves (Tables 2 and 4). However, CO_2 effluxes from fields where the excavation-drier method was used were significantly lower than from fields exploited with the milling method (Tables 2 and 4). The milling method's stockpiles emitted very large amounts of CO_2, while CO_2 effluxes from those of the excavation-drier method were much smaller (Table 4). Biomass driers emitted only small amounts of CO_2 (Table 4), and only during summer when the driers were in use. CO_2 effluxes in winter were on average ca. 15% of annual effluxes, excluding stockpiles, which occasionally produced higher CO_2 effluxes in winter (Tables 5 and 6). Positive, but non-significant, correlation between the ash content of topsoil (0–20 cm) and CO_2 effluxes was found ($r_P = 0.60, p = 0.09$).

The response of CO_2 efflux to T_5 varied markedly among the sites and extraction-area types (extraction reserve, fields extracted with excavation-drier method and milling method) (Fig. 2). The northernmost site (Kortessuo) had the highest response to T_5 and the southernmost (Isosuo) the lowest in all extraction area types (Fig. 2). This trend in the response of CO_2 efflux to T_5 resulted in increased CO_2 effluxes at the northernmost site (Kortessuo) (Tables 4–6).

Table 2. CO_2-flux differences between extraction reserves and extraction fields (EM and MM). Statistical test used was one-way ANOVA with post hoc test (Tukey HSD). MM = milling method. NM = excavation-drier method.

	df	*F*	*p*
Isosuo			
Extraction reserve	8,216		
EM field	8,216	49.41	< 0.001
MM field	8,216	26.08	< 0.001
Aitoneva			
Extraction reserve	8,216		
EM field	8,216	25.11	0.001
MM field	8,216	9.87	0.012
Kortessuo			
Extraction reserve	8,216		
EM field	8,216	111.37	< 0.001
MM field	8,216	60.34	< 0.001

However, CO_2 effluxes from the Aitoneva site were smaller than from the southernmost Isosuo site (Tables 4–6), although the response of CO_2 efflux to T_5 was higher in the Aitoneva site than in the southernmost Isosuo site (Fig. 2).

All of the studied sites and areas were CH_4 sources, and the variation in annual CH_4 fluxes was large (Table 4). CH_4 fluxes were significantly lower (Kruskall-Wallis test: $\chi^2_2 = 55.67$, $p < 0.001$) in Isosuo and Kortessuo sites after peat extracting with both methods (Table 4). In contrast to other sites, CH_4 fluxes from the milled peat fields at the Aitoneva site were even higher than CH_4 fluxes from the extraction reserve (Table 4). Variation in the CH_4 fluxes

Table 3. Regression models for CO_2 efflux (g m^{-2} h^{-1}) (CO_2 efflux = $ae^{b \times T_5}$) for the three study sites. All results are significant at $p < 0.0001$. MM = milling method, NM = excavation–drier method.

	a (± SE)	*b* (± SE)	r^2
Isosuo			
Extraction reserve	0.1845 (± 0.0346)	0.0435 (± 0.0100)	0.50
EM field	0.0258 (± 0.0052)	0.1028 (± 0.0101)	0.88
MM field	0.0739 (± 0.0093)	0.0557 (± 0.0056)	0.83
Aitoneva			
Extraction reserve	0.0493 (± 0.0182)	0.1213 (± 0.0208)	0.68
EM field	0.0169 (± 0.0029)	0.1195 (± 0.0097)	0.90
MM field	0.0312 (± 0.0065)	0.1039 (± 0.0110)	0.84
Kortessuo			
Extraction reserve	0.1267 (± 0.0259)	0.1213 (± 0.0131)	0.85
EM field	0.0082 (± 0.0032)	0.1784 (± 0.0263)	0.75
MM field	0.0533 (± 0.0124)	0.1003 (± 0.0142)	0.67

Table 4. Annual mean ± SE GHG fluxes at the three study sites during 2006–2007. Annual CO_2-C effluxes for peat extraction areas excluding stockpiles and biomass drier are the sums of seasonal and winter fluxes. MM = milling method, NM = excavation-drier method.

	CO_2-C (g m^{-2})	CH_4 (mg m^{-2} d^{-1})	N_2O (μg m^{-2} d^{-1})
Isosuo			
Extraction reserve	413 ± 34	21.9 ± 6.6	600 ± 114
EM field	121 ± 9	2.0 ± 1.0	214 ± 77
MM field	188 ± 16	7.1 ± 2.8	474 ± 96
MM stockpile	3234 ± 362	5.5 ± 1.0	873 ± 201
EM stockpile	115 ± 13	0.6 ± 0.3	185 ± 33
Biomass drier	72 ± 7	0.8 ± 0.2	238 ± 49
Aitoneva			
Extraction reserve	240 ± 33	4.2 ± 0.7	4845 ± 801
EM field	83 ± 6	1.7 ± 0.5	512 ± 114
MM field	123 ± 12	6.4 ± 2.2	504 ± 87
MM stockpile	2985 ± 254	21.6 ± 6.6	1104 ± 217
EM stockpile	244 ± 27	0.8 ± 0.1	324 ± 92
Biomass drier	49 ± 6	0.6 ± 0.2	635 ± 103
Kortessuo			
Extraction reserve	565 ± 39	36.3 ± 9.3	666 ± 69
EM field	78 ± 8	1.0 ± 0.9	317 ± 58
MM field	182 ± 17	4.7 ± 2.7	746 ± 179
MM stockpile	2796 ± 256	3.9 ± 1.3	975 ± 195
EM stockpile	164 ± 16	0.8 ± 0.2	244 ± 31
Biomass drier	58 ± 5	0.9 ± 0.2	333 ± 52

Table 5. Seasonal (May–October) mean ± SE GHG fluxes at the three study sites during 2006–2007. Seasonal CO_2-C effluxes for peat extraction areas excluding stockpiles and biomass drier are hourly-modeled effluxes, and their SEs are the standard errors of model estimates. MM = milling method, NM = excavation-drier method.

	CO_2-C (g m^{-2})	CH_4 (mg m^{-2} d^{-1})	N_2O (μg m^{-2} d^{-1})
Isosuo			
Extraction reserve	344 ± 61	31.9 ± 6.4	840 ± 151
EM field	104 ± 16	3.4 ± 1.5	192 ± 108
MM field	160 ± 23	13.3 ± 5.1	617 ± 130
MM stockpile	2738 ± 253	4.8 ± 0.9	824 ± 154
EM stockpile	159 ± 13	0.3 ± 0.2	258 ± 41
Biomass drier	72 ± 7	0.8 ± 0.2	238 ± 49
Aitoneva			
Extraction reserve	206 ± 63	8.1 ± 1.2	7290 ± 1039
EM field	69 ± 10	3.4 ± 0.8	712 ± 188
MM field	105 ± 22	6.2 ± 1.0	751 ± 107
MM stockpile	3748 ± 278	18.3 ± 4.4	1774 ± 323
EM stockpile	349 ± 27	0.2 ± 0.1	603 ± 176
Biomass drier	49 ± 6	0.6 ± 0.2	635 ± 103
Kortessuo			
Extraction reserve	478 ± 66	67.1 ± 15.9	715 ± 79
EM field	64 ± 13	1.7 ± 1.6	305 ± 29
MM field	158 ± 28	8.1 ± 4.7	946 ± 271
MM stockpile	3008 ± 275	6.4 ± 2.4	1401 ± 313
EM stockpile	168 ± 10	1.0 ± 0.2	244 ± 26
Biomass drier	58 ± 5	0.9 ± 0.2	333 ± 52

in extraction fields of both methods between different sites was small (Table 4). Stockpiles created via the milling method were rather large sources of CH_4 only at the Aitoneva site; at other sites, the stockpiles of both methods were only small CH_4 sources (Table 4). CH_4 fluxes from biomass driers were very small (Table 4). CH_4 fluxes in winter were on average ca. 15% of annual effluxes, excluding stockpiles (Tables 5 and 6). They were remarkable especially from stockpiles, but occasionally also from other areas such as milled peat fields (Tables 5 and 6). No significant correlation was found between CH_4 fluxes and soil factors.

All the study sites emitted N_2O, but variation in annual N_2O fluxes among the areas was large. Especially annual N_2O fluxes from the extraction reserves varied from rather small to very large (Table 4). N_2O fluxes were significantly lower only at the Aitoneva site after peat extraction as compared with the reference situation with both methods used (Kruskall-Wallis test: $\chi^2_2 = 119.23$, $p < 0.001$; Table 4). N_2O fluxes were not significantly lower at the extracted Isosuo and Kortessuo sites, and at the Kortessuo site even slightly higher N_2O fluxes were observed from milled peat fields as compared with those from extraction reserve (Table 4). At all sites, stockpiles were rather small sources of N_2O, thus differing from other GHGs (Table 4). N_2O fluxes in winter were remarkable especially at the Isosuo and Kortessuo sites, where winter N_2O fluxes constituted 40% and 45% of the annual fluxes, respectively (Tables 5 and 6). At the Aitoneva site, winter N_2O fluxes were only 27% of the summer fluxes (Tables 5 and 6). N_2O fluxes from biomass driers were unexpectedly high (Table 4). A significant negative correlation was found between the C/N ratio of topsoil (0–20 cm) and N_2O fluxes ($r_p = -0.68$, $p = 0.045$), i.e., N_2O fluxes decreased exponentially with increasing C/N ratios.

Long-term climatic impact analyses

The global warming potential (GWP) is a calculational warming or cooling effect in the atmosphere due to the combined GHG emissions (CO_2 equivalents) from the different study sites with the considered peat-extraction chains and also due to the avoided GHG emissions from the energy production using fossil fuels (mainly with coal). The factors increasing the GWP value are the GHG emissions from peat combustion, emissions from peat extraction (working machines

Table 6. Wintertime (November–April) mean ± SE GHG fluxes at the three study sites during 2006–2007. MM = milling method, NM = excavation-drier method.

	CO_2-C (g m^{-2})	CH_4 (mg m^{-2} d^{-1})	N_2O (μg m^{-2} d^{-1})
Isosuo			
Extraction reserve	69 ± 8	11.9 ± 6.7	359 ± 77
EM field	17 ± 2	0.6 ± 0.5	235 ± 45
MM field	28 ± 9	0.8 ± 0.5	331 ± 62
MM stockpile	3730 ± 471	6.1 ± 1.1	921 ± 248
EM stockpile	72 ± 13	0.8 ± 0.3	111 ± 25
Aitoneva			
Extraction reserve	35 ± 3	0.3 ± 0.1	2400 ± 563
EM field	14 ± 1	0.02 ± 0.14	311 ± 40
MM field	18 ± 2	6.5 ± 3.4	256 ± 66
MM stockpile	2223 ± 230	24.9 ± 8.8	434 ± 110
EM stockpile	139 ± 28	1.3 ± 0.1	44 ± 7
Kortessuo			
Extraction reserve	87 ± 13	5.4 ± 2.7	617 ± 58
EM field	14 ± 3	0.3 ± 0.2	328 ± 86
MM field	25 ± 6	1.2 ± 0.6	546 ± 87
MM stockpile	2585 ± 237	1.4 ± 0.2	548 ± 76
EM stockpile	161 ± 22	0.5 ± 0.1	244 ± 36

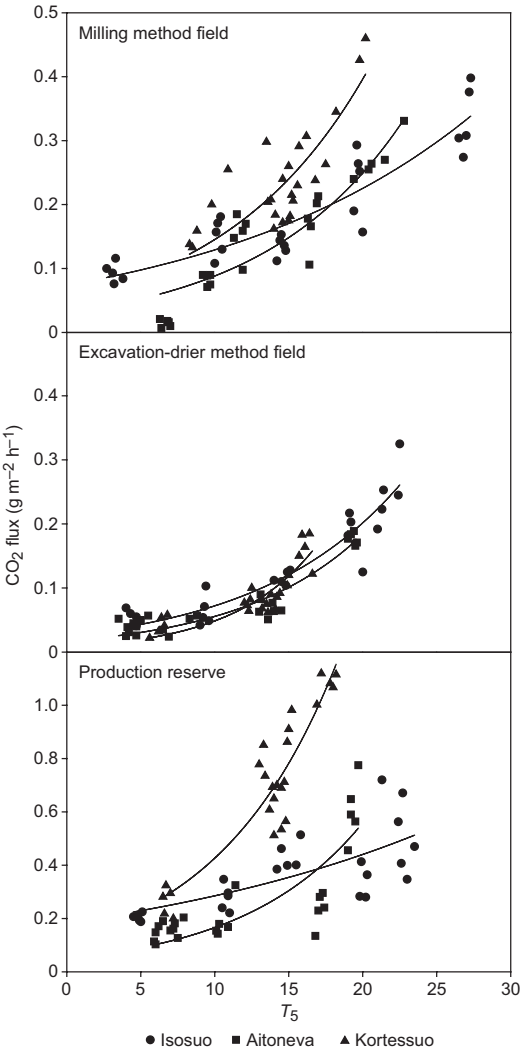

Fig. 2. Relationships between CO_2 effluxes and soil T_5 (5 cm below the soil surface). The regression lines equation is CO_2 efflux = $ae^{b \times T_5}$. *See* Table 2 for the parameter values and SEs.

and transport) and from the extraction reserves (extraction reserve emissions) due to peat extraction (Fig. 3). The factors decreasing the GWP value are the avoided GHG emissions from the energy production with fossil fuels (coal), carbon sequestration in the areas after peat extraction and the avoided reference emissions from the peat extraction areas (Fig. 3).

If the GHG emissions are as high as in the studied extraction reserves and peat is used instead of coal to produce a certain amount of energy (avoided emissions subtracted), the GWP values will be negative (cooling effect) (Figs. 3 and 4). If peat had been produced from the "average" drained peatland (annual CO_2 effluxes 224 g m^{-2}, CH_4 fluxes 2.7 mg m^{-2} d^{-1} and N_2O fluxes 278 μg m^{-2} d^{-1} (Kirkinen *et al*. 2007, 2010), the GWP values would have been close to zero regardless of the extraction method used (Fig. 4). The excavation-drier method generates a slightly reduced climatic impact as compared with the milling method which prevails in all areas (Fig. 4). Additionally, the after-extraction alternatives have little effect on the GWP (Figs. 3 and 4). Instead, the type of extraction reserve has a much larger effect on the GWP than the extraction method or the after-extraction treatment used (Fig. 4).

Discussion

The edge areas used as extraction reserves in this study appeared to be large sources of GHGs. CO_2 effluxes from the extraction reserves were of the same magnitude as from organic croplands or nutrient-rich forestry-drained peatlands. In this study, we measured rather similar CO_2 effluxes from the extraction reserves to those reported by Maljanen *et al*. (2007) for organic croplands. For further comparison, both afforested organic croplands (Mäkiranta *et al*. 2007) and nutrient rich forestry-drained peatlands (Minkkinen *et al*. 2007a, Ojanen *et al*. 2010) also emitted rather similar amounts of CO_2. Why are the edge areas such large sources of CO_2? They are often disturbed, well-drained areas to which litter and mineral soil have been carried with peat extraction machines and from ditch bottoms. Especially mineral soil addition is closely related to the higher ash content (Wall and Hytönen 1996) and higher pH (Pessi 1962) of surface peat, which may accelerate microbial activity and the decomposition of organic matter, and thus CO_2 effluxes.

CO_2 effluxes from milled peat fields and stockpiles were of the same magnitude as those measured by Ahlholm and Silvola (1990) and Nykänen *et al*. (1996). However, CO_2 effluxes from the excavation-drier-method stockpiles were much lower than effluxes from milled ones,

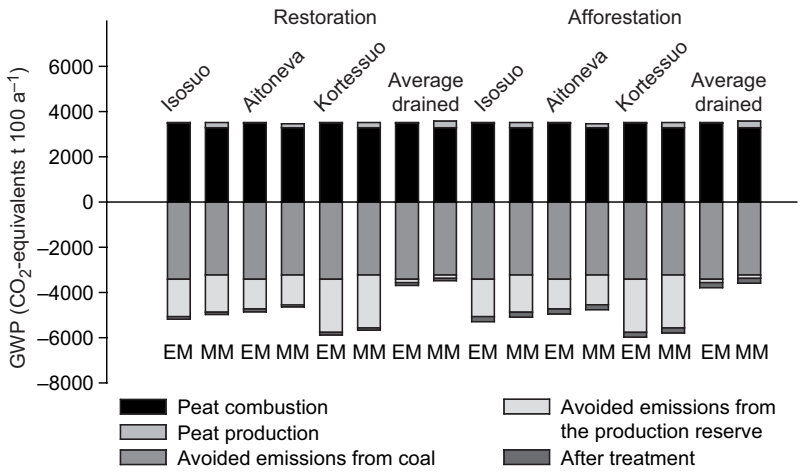

Fig. 3. Factors affecting the global warming potentials (GWP, CO_2 equivalents ha^{-1} a^{-1} in a 100 year time span) at different study sites for the excavation-drier method (EM) and the milling method (MM) with two different after-treatments. The very low GWPs from peat transport and indirect emissions cannot be seen at the of the graph.

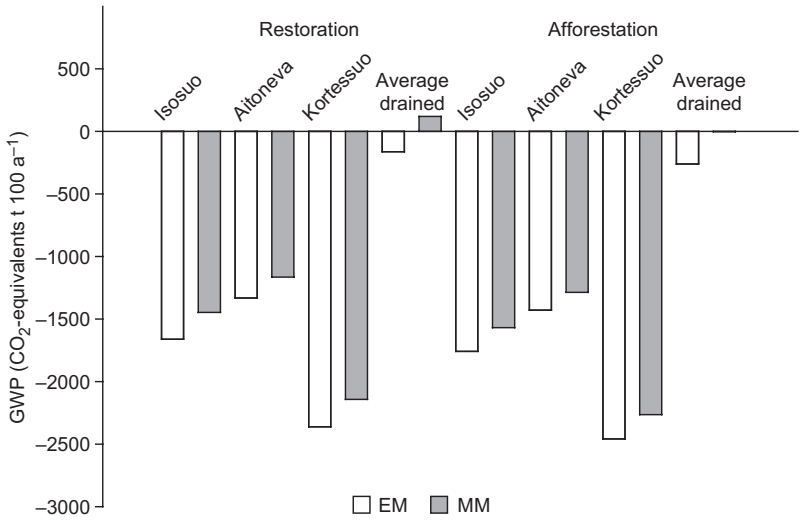

Fig. 4. Total global warming potentials (GWP, CO_2 equivalents ha^{-1} a^{-1} in a 100 year time span) at different study sites for the excavation-drier method (EM) and the milling method (MM) with two different after-treatments.

probably due to the "sod-peat" like properties of the extracted peat. This result was also found for CH_4 and N_2O fluxes (Nykänen *et al*. 1996).

CO_2 effluxes from fields extracted using the excavation-drier method were significantly smaller than effluxes from milled peat fields. One reason for the lower CO_2 effluxes may be the removal of the whole peat layer along with decomposing microbes during one harvesting season in the excavation-drier method, but only 5–20 cm of surface peat per year in the milling method. The difference between the methods used may be even larger, if we take into account the loose, well-aerated milled layer that may associate with high CO_2 effluxes (Alm *et al*. 2007a).

The highest response to temperature was observed at the northernmost site. A similar climatic trend was found by Minkkinen *et al*. (2007) for forestry-drained peatlands, and also for upland forest soils in Europe (Medlyn *et al*. 2005). The probable explanation for the higher response to temperature northwards is the adaptation of northern heterotrophic decomposer populations to cold conditions, and responding rapidly to increasing temperature, as indicated by the results of Domisch *et al*. (2006).

CH_4 fluxes from the extraction reserves were clearly higher than for instance from organic croplands (Maljanen *et al*. 2007), but the variation in CH_4 fluxes was also large. Also affor-

ested organic croplands emitted less CH_4 than the extraction reserves in this study (Mäkiranta *et al*. 2007). CH_4 fluxes from forestry-drained peatlands were of the same magnitude as those from the extraction reserves (Minkkinen *et al*. 2007b, Ojanen *et al*. 2010). However, CH_4 fluxes from pristine mires can be much higher than those from the extraction reserves (Saarnio *et al*. 2007).

CH_4 fluxes measured from milled fields and stockpiles were generally low and they were in line with those measured by Nykänen *et al*. (1996). However, CH_4 fluxes from stockpiles can be rather high per unit area, especially in winter. Generally, the high CH_4 fluxes are related to rather rarely occurring high moisture content in the stockpiles, which may create low oxygen conditions suitable for active methanogenesis (Nykänen *et al*. 1996). Also, the total area of stockpiles is really small ast compared with other extraction area types, and thus total CH_4 fluxes also remain low.

High N_2O fluxes from the Aitoneva site extraction reserve were of the same magnitude as from organic croplands (Maljanen *et al*. 2007), afforested organic croplands (Mäkiranta *et al*. 2007) and nutrient-rich forestry-drained peatlands (Martikainen *et al*. 1993). The lowest N_2O fluxes from the extraction reserves in our study were of the same magnitude as fluxes from nutrient-poor forestry-drained peatlands (Martikainen *et al*. 1993, Ojanen *et al*. 2010).

N_2O fluxes measured from milled peat fields were generally low and of the same magnitude as measured by Nykänen *et al*. (1996). Also Nykänen *et al*. (1996) reported quite low N_2O fluxes from stockpiles, which was in line with our results. However, N_2O fluxes from biomass driers were unexpectedly high especially at the Aitoneva site, although the measured peat layer on the drier was often extremely dry, and biomass driers emitted N_2O only during the summer when the driers were in use. Winter fluxes of N_2O generally comprised a higher proportion of annual fluxes than wintertime fluxes of other GHGs, which is in line with the studies of e.g. Maljanen *et al*. (2007) and Mäkiranta *et al*. (2007).

Conclusions

In all areas, energy-peat extraction with the excavation-drier method results in a smaller long-term climatic impact as compared with that caused by the prevailing milling method. However, the peat extraction method used and also after-extraction treatments affect the GWP only little. The probable explanation to the unexpectedly small difference between the peat extraction methods is the much larger and simultaneously open peat extraction area in the milling method. Although GHG fluxes per area from the fields of the excavation-drier method were significantly smaller than those from milled fields, GHG fluxes from the milled fields were, however, significantly lower than the extraction reserve fluxes. Thus, a 20 times larger open peat extraction area with decreased GHG fluxes in the milling method largely levels out the differences in the climatic impacts of the two methods. However, here we have not considered the potential for the early start of carbon sequestration into after-use crops in the excavation-drier method, and this would create a somewhat larger difference between the two methods.

The type of extraction reserve has a much larger effect on the GWP than the peat extraction method. The use of peatlands with high original GHG emissions will create a significantly lower GWP than the use of "average" drained peatlands. Thus, it is important to direct peat extraction to areas — such as organic croplands, the edges of peat extraction areas or nutrient-rich forestry-drained peatlands — that are large sources of GHGs. Such direction of peat extraction would reduce the long-term negative climatic impact of energy peat utilization. The extraction method alone appears to have only a minor effect on GWP, but the excavation-drier method can also be used in areas which are not viable for utilisation with conventional peat extraction methods.

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