DISSERTATIONES GEOGRAPHICAE UNIVERSITATIS TARTUENSIS

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JÜRI-OTT SALM

Emission of greenhouse gases CO_2, CH_4, and N_2O from Estonian transitional fens and ombrotrophic bogs: the impact of different land-use practices

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II Kimmel, K., Kull, A., Salm, J.-O., Mander, Ü. 2009. The status, conservation and sustainable use of Estonian wetlands. Wetlands Ecology and Management 18(4): 375–395.

III Salm, J.-O., Maddison, M., Tammik, S., Soosaar, K., Truu, J., Mander, Ü. 2012. Emissions of CO_2, CH_4 and N_2O from undisturbed, drained and mined peatlands in Estonia. Hydrobiologia. DOI: 10.1007/s10750-011-0934-7.

IV Mander, Ü., Järveoja, J., Maddison, M., Soosaar, K., Aavola, R., Ostonen, I., Salm, J.-O. 2012. Reed canary grass cultivation mitigates greenhouse gas emissions from abandoned peat extraction areas. Global Change Biology Bioenergy. DOI: 10.1111/j.1757-1707.2011.01138.x.

Author's contribution

Publication I: The author is responsible for the data collection (about 70%), analyses (about 70%) and manuscript preparation (about 80%).

Publication II: The author is partly responsible for the data collection (about 10%), analyses (about 10%) and manuscript preparation (about 10%).

Publication III: The author is responsible for the fieldwork and data collection (about 70%), analyses (about 70%) and manuscript preparation (about 80%).

Publication IV: The author is partly responsible for the fieldwork and data collection (about 10%).

ABSTRACT

In this PhD dissertation, emissions of greenhouse gases (GHG) CO_2, CH_4 and N_2O are estimated according to field measurements in Estonian transitional fens and ombrotrophic bogs under different land use practices. The effects of drainage, peat extraction and reed canary grass (*Phalaris*) cultivation on GHG emission and carbon balance are evaluated. Investigation of the literature indicated that compared to CO_2 sequestration in non-altered peatlands, drainage and lowered water level leads to a significant increase in CO_2 emissions in all peatland types. Methane emissions showed lower values in drained as opposed to undrained mires. There are fewer data on N_2O emissions, but these indicate a significant increase in gas emissions with drainage, while it has been estimated to be small and inconsequential in transitional mires and bogs.

Closed chamber based sampling lasted from October 2008 to October 2010 in 10 peatlands in Estonia, covering areas with different land use practices: natural (5 study sites), drained (6 sites), abandoned peat mining (6 sites) and active peat mining areas (5 sites), *Phalaris* cultivation areas (2 sites), and a fen meadow under strong drainage influence. Results from peat extraction areas, including the *Phalaris* sites, corresponded to the results obtained from other studies. Emission values of CH_4 and N_2O from the study sites correspond to other studies of that kind, also.

The median values of cumulative annual soil effluxes of CO_2-C from natural, drained, abandoned, active extraction, *Phalaris*, and fen meadow sites were 1563 (ranging from 1167 to 2127), 1921 (507–3276), 1863 (683–4322), 1741 (1363–4382), 4783 (3583–5983), and 11,353 kg CO_2-C ha^{-1} y^{-1} respectively.

The median values of cumulative annual soil effluxes of CH_4-C from natural, drained, abandoned, active extraction, *Phalaris*, and fen meadow sites were 71.1 (ranging from 23.9 to 120.8), 23.7 (8.1–137.1), 0.06 (–4.8–20.4), 0.12 (–0.1–6.1), 0.30 (0.20–0.31), and –1.23 kg CH_4-C ha^{-1} y^{-1} respectively.

The median values of cumulative annual soil effluxes of N_2O-N from natural, drained, abandoned, active extraction, *Phalaris*, and fen meadow sites were –0.05 (ranging from –0.06 to 0), –0.01 (–0.06–0.06), 0.17 (0.02–1.06), 0.19 (0.06–3.97), –0.05 (–0.09–0.02), and 2.64 kg N_2O-N ha^{-1} y^{-1} respectively.

Based on the results from this study and the corresponding results from other studies, it is estimated that peat extraction has raised almost ten-fold (from accumulation of 24,405 to emission of 191,499 t CO_2 yr^{-1}) the radiative forcing of mire areas under peat extraction in Estonia. Emissions and biomass measurements from *Phalaris* sites showed that these areas had changed from net sources to net sinks of carbon.

1. INTRODUCTION

The landscape and climate have favoured the formation of peatlands, which constitute a dominant element in the Estonian landscape, but due to human activities, the area of natural mires is decreasing (Paal *et al.,* 1999; Paal & Leibak, 2011). Destruction of mires and alteration of peatlands due to human activities may lead to the changing role (source *versus* sink) of peatlands in respect to greenhouse gas emissions and their share in greenhouse effect. Although Estonia has achieved good results in wetland protection (including mires) there are still crucial challenges: first, the addressing of drained wetland areas that have become sources of greenhouse gases; second, attaining sustainable use of peat resources and ensuring the restoration of cut-away peatland areas (II – Kimmel *et al.,* 2009). Additional and constant pressure on mires comes from oil shale mining and processing (Karofeld & Ilomets, 2008). The main cause for the reduction in mire areas has been drainage for agricultural and forestry purposes, and in addition there are about 30,000 ha of peat extraction areas (Ramst & Orru, 2009). This has also affected the carbon (C) balance of Estonian mires – property attributed to ecosystem services in the form of carbon storage.

On a global level, nearly 30% of soil carbon is held in northern peatlands (Gorham, 1991), stored at an estimate rate of 23 g C m^{-2} y^{-1} (Gorham, 1995). Peatlands have accumulated 34–46% of the roughly 796 Gt of C currently held in the atmosphere as CO_2 (IPCC, 2007; Limpens *et al.,* 2008). Boreal and subarctic peatlands contain about 20% of the global terrestrial C-stock in their aboveground biomass and belowground organic matter (Post *et al*., 1982; Janzen, 2004).

Several investigations have been carried out in order to estimate greenhouse gas fluxes and the C balance on a national scale, e.g. Finland (see Minkkinen *et al*., 2002; Alm *et al*., 2007), Sweden (see Nilsson *et al*., 2001; von Arnold *et al*., 2005a, b) and North America (see Bridgham *et al*., 2006). One important factor is the estimation of the proportion of emissions from peat mining, agricultural and forestry drained areas, including life-cycle analysis in order to determine the net greenhouse gas (GHG) emissions from different land-use practices. This includes peat extraction, wetlands restoration, reed canary grass (*Phalaris arundinacea* L.*)* cultivation, afforestation and the restoration of abandoned peat extraction areas or other drained areas. It is also necessary to include entire rotation periods and the estimation of the GHG effect of harvested products (Maljanen *et al*., 2010).

This study included investigations based on literature studies (I – Salm *et al*., 2009; II – Kimmel *et al*., 2009), field measurements of GHGs from peatlands with different land use practices (III – Salm *et al*., 2012), and an estimation of the C balance and global warming potential (GWP) of reed canary grass cultivation (IV – Mander *et al*., 2012). Further studies include a life-cycle assessment of the cultivation of *Phalaris* (Järveoja *et al*., 2012). There are also opportunities for the assessment of the effect of wetland restoration, as on one of the research sites of the present study – Kuresoo in Soomaa National Park – activities have begun in order to restore the natural habitat in the drained part of this mire.

The aim of the study is to estimate emissions of greenhouse gases (GHG) CO_2, CH_4, and N_2O, and the effects of drainage and peat extraction on these processes in Estonian transitional fens and ombrotrophic bogs. Field investigations using the closed chamber method provide additional information on the effect of drainage and peat extraction on a local scale, and the GHG balance in Estonian peatlands. In addition, the impact of reed canary grass cultivation on GHG emissions was estimated.

1.1. Areal estimation of transitional fens and bogs of Estonia and emissions due to land use practices

Approximately 70% of Estonian peatlands have been affected by drainage, probably to the extent that peat accumulation has ceased, and the mineralization of organic matter has replaced carbon accumulation. The total area of Estonian transitional fens and ombrotrophic bogs was estimated to be 339,772 ha, of which at least 51,978 ha has been drained (I). According to Paal & Leibak (2011), the area of preserved mires is even smaller – based on field inventories in 2009 and 2010, mires form at least 240,000–245,000 ha or ca 5.5% of Estonian territory, which is 2.6–2.8 less than 60 years ago. Data can be used for comparison with results from the present thesis after the completion of a field inventory of different types and the updating of the mire database in 2013.

On the basis of the literature data (I), annual efflux from drained areas was estimated to be from 419,000 to 676,000 t CO_2 equivalents (eq) y^{-1} and –141,000 to 380,000 t CO_2 eq y^{-1} from the undrained area. We calculated the global warming potential if Estonian peatlands were to be hydrologically restored. This is 2.3 to 2.7 times lower than the present total emission of 278,000 to 1,056,000 t CO_2 eq y^{-1}.

Updated information on the areal coverage of mires, studies covering net ecosystem emission (NEE), life-cycle analyses of peat use and forest products could alter this estimate significantly. This estimate excluded peat mining areas, which are mainly established on transitional fens and ombrotrophic bogs. Although their areal coverage is small, there is significant potential for GHG emissions, namely CO_2 effluxes. According to the revision of peat extraction sites, the area of abandoned and active peat mining sites is 9371 and 19,574 ha respectively (Ramst & Orru, 2009).

2. MATERIALS AND METHODS

2.1. Study sites

Gas fluxes were measured in five mire complexes in western, central and eastern Estonia (III, IV, Fig. 1, Table 1). The study sites represented transitional fens and ombrotrophic bogs and differed according to land use practices. The following management types were distinguished: natural mire (N), drained peatland (D), abandoned peat extraction area (A, BS), active peat extraction area (M), peat extraction area used for reed canary grass (*Phalaris*) cultivation (P) and fen meadow (FM).

In each mire, several different land use practices were presented:

I Kuresoo and Valgreraba in Soomaa National Park consisted of natural areas with minimum impact from drainage and sites drained for forestry. In Soomaa, nine sites were studied: in Valgeraba two areas belonging to the wooded hummock bog subtype (1N, 2N) beside the area under forestry drainage belonging to the mesotrophic bog forest site type (6D, 7D); in Kuresoo, gas emissions from undisturbed areas of the hollow-ridge bog subtype were measured from hollows and hummocks (3N, 4N), and three sites were selected from an area under strong drainage influence – hollow with rare plant cover (8D), hummocks with (10D) and without *Eriophorum vaginatum* (9D) (III).

II The Sangla study site belongs to the mesotrophic bog forest site type under strong drainage influence beside the peat extraction area (11A) (III).

III The Kasesoo and Oru peat extraction areas in Puhatu mire consisted of peat extraction areas – an active extraction area that was taken into use after 20 years of abandonment (16M), an active extraction area with slightly and highly decomposed peat (17M and 18M), areas that had been abandoned from peat extraction for five years (13A) and twenty years (12A) and had strong drainage influence and sparse vegetation, and a wooded hummock bog affected by drainage (5D) (III).

IV In Hiiesoo mire four study sites were investigated: abandoned peat extraction areas that had not been mined for ten years (14A) and twenty-five years (15A) and had strong drainage influence and sparse vegetation, and active peat extraction areas with undecomposed (20M) and slightly decomposed peat (19M) (III).

V The Lavassaare peat extraction area is located in Maima bog in western Estonia. Four sites were investigated: a cultivated fen meadow (FM) and a natural raised bog (NB), an abandoned peat extraction site with bare peat (BS) adjacent to two sites of experimental *Phalaris* fields (P) consisting of fertilized (fP) and non-fertilized areas (nfP) (IV).

In the peat extraction areas, the vacuum mining method was used.

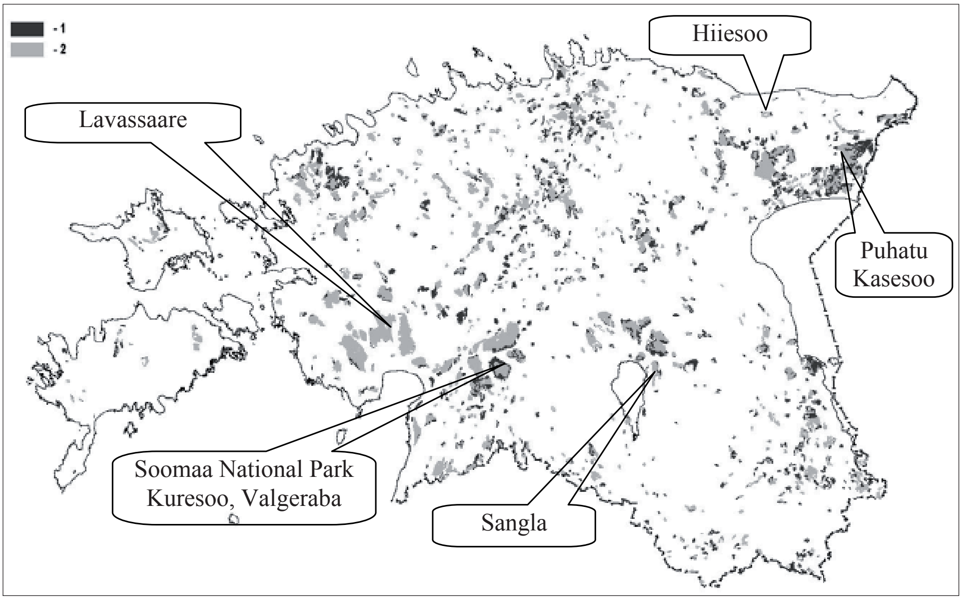


Figure 1. Distribution of transitional fens and oligotrophic bogs and location of study sites in Estonia.

1 – Areas affected by drainage;
2 – Natural areas or areas not included in databases of drained areas.

2.2. Field measurements

2.2.1. Gas sampling and analyses

The closed-chamber method (Hutchinson & Livingston, 1993) was used for the measurement of CO_2-C, CH_4-C and N_2O-N fluxes. Gas samplers (closed chambers with a cover made of PVC, height 50 cm, Ø 50 cm, volume 65 l, sealed with a water-filled ring on the soil surface, painted white to avoid heating during application) were installed on five pre-installed rings per study site. In mid-summer additional 1.2 m high PVC chambers were used for the *Phalaris* sites. Gas sampling was carried out on a monthly basis from October to November 2008, January to December 2009 and March to October 2010. Each area was covered for at least a 12-month period, and cumulative annual soil effluxes are based on 10-month or 12-month data. No field measurements were carried out in December 2008 and from January to February 2010 due to unfavourable weather conditions – low temperatures and deep snow conditions. In the winter season, chambers were placed on the snow when there was snow coverage (up to 25 cm).

Table 1. Main characteristics of investigated peatlands. Site types are numbered and determined based on land use: natural (N, NB), drained (D), abandoned (A), active (mined) peat extraction (M), the cultivated fen meadow (FM), abandoned peat extraction site with bare peat (BS) neighboring to two sites of experimental *Phalaris* fields (P). Water table levels are measured on monthly bases; average, minimum and maximum levels are presented indicating water level below the ground surface. Peat decomposition describes upper 50 cm of the peat profile at the study sites (values according to von Post index;).

Peatland		Hiiesoo				Kasesoo			Kuresoo					Puhatu			Sangla	Valgeraba				Lavassaare				
Geo-graphical coordinates		N 59°21'5" E 27° 6'23"				N 59° 8'30" E 27°40'5"			N 58°30'10" E 25° 9'44"					N 59°15'21" E 27°38'55"			N58°19'35" E 26°13'8"	N 58°26'48" E 25°14'23"				N 58°34'20" E 24°23'15"				
Number of sites		4 sites				3 sites			5 sites					3 sites			1 site	4 sites				4 sites				
Site type No & code		14A	15A	19M	20M	5D	12A	16M	3N	4N	8D	9D	10D	13A	17M	18M	11A	1N	2N	6D	7D	NB	FM	BS	fP	nfP
Water table depth (cm)	Ave	50	25	33	41	15	70	81	3	6	1	0	4	79	≥60	57	65	7	4	13	13	19	>150	26	27	16
	Min	84	61	70	70	24	120	131	10	13	10	7	20	108	ND	88	78	16	15	26	29	38	ND	71	45	31
	Max	0	0	1	0	3	10	23	6	2	7	10	–3	29	ND	0	55	6	6	4	5	6	ND	0	6	1
Peat decom-position		1–5	2–5	1–5	2–5	1–4	1–5	3–5	1–2	1–2	1	1	1	1–5	3–5	6–7	7–8	1–2	1–2	3–6	3–6	2	9	7	7	7
Peat depth (m)		1.50	1.70	1.45	2.60	6.60	3.80	2.60	2.15	2.15	2.20	2.20	2.20	2.80	2.70	0.60	2.60	1.05	1.05	0.95	0.95	3.00	0.70	1.20	0.75	0.6
C : N ratio		49	57	49	49	41	43	27	50	83	87	49	46	39	26	42	17	57	44	16	16	35	15	22	20	20

During the vegetation period (April to September) of 2009 and 2010 measurements were conducted at sites 3N, 4N, 8D, 9D, 10D, and 11A. A comparison of the results of two year measurements are presented in Table 2.

The measurement consisted of 3 gas samples collected during 1-hour measurement (0, 30, 60 minutes). For CO_2 measurements at the sites in Lavassaare, an additional sample was taken 3 min after the installation of chambers on rings. Measurements were carried out during the daylight period. Pilot measurements were also performed at night at study site 11A, but the results did not differ from the daily fluxes. Gas was collected into pre-evacuated (0.3 mbar) 100 mL glass bottles and taken to the laboratory of the Department of Geography of the Institute of Ecology and Earth Sciences at the University of Tartu. The gas concentration in the collected air was determined using the gas chromatography system (electron capture detector and flame ionization detector; Loftfield *et al*., 1997) Shimadzu GC-2014. Emission rates for one site were calculated as the average or medium of the results from 5 chambers per site.

The GWP of CO_2, CH_4 and N_2O in CO_2 equivalents was calculated using the radiative forcing coefficients of 1, 25, and 298 respectively (IPCC, 2007).

2.2.2. Soil and water analysis

During each gas sampling session at each site, the depth of the groundwater table (cm) in the observation wells (∅ 50mm, up to 1.5 m deep PVC pipes perforated and sealed in a lower 0.5 m part) and soil temperature were measured at 4 depths (10, 20, 30, and 40 cm) and at the soil surface. During the winter period it was sometimes not possible to measure these characteristics due to the frozen surface and low temperatures.

Soil chemical content (Total Carbon, Total Nitrogen, Total Sulphur, and Total Phosphorus), and for water, pH, BHT_7, NH_4^-, NO_2^-, NO_3^-, N_{org}, N_{total}, SO_4^-, dissolved organic carbon (DOC), O_2 and redox potential were measured at sites under peat extraction; C and N content was determined at all sites. Chemical analyzes were carried out at Eesti Keskkonnauuringute Keskus Ltd (EKUK).

The depth of peat was measured and the profile described according to the von Post index.

2.2.3. Plant analysis

In all areas, a plant inventory was carried out and its main characteristics described (III, IV).

For the biomass analysis, *Phalaris* sites were measured in order to estimate aboveground and belowground biomass production in fertilized and non-fertilized sites (IV). The grass litter from the sites was sampled in May 2010 and April 2011 from 1 m^2 plots in five replicates. Aboveground and belowground biomass production was measured at the end of September 2010 (peak production) and at the beginning of April (after the snow melt). Aboveground biomass was collected from the sites of litter sampling plots. The collected litter and aboveground biomass was dried in the lab for 72 h at 70°C in a Gallenkamp Sanyo OMT oven, and dry weight (dw) was determined using Kern GS 6200-1 analytical balances. Before drying, the weight of the air-dry litter was determined.

Belowground biomass was measured at each chamber, up to a depth of 25 cm and using a 10×10 cm auger. Soil samples were stored at 4°C until processed. The content of total C, total N, and P in aboveground and belowground parts and in litter were measured at the Tartu lab of EKUK.

2.2.4. Statistical analysis of data

The normality of variable distributions was checked using the Kolmogorov–Smirnov and Lilliefors tests, and Shapiro–Wilk's test was used to test the hypothesis for normality (III, IV), and the case of conflicting results from the Lillefors and Shapiro-Wilk's tests, the Chi-square test was also used (IV). In the case of the gas analyses, the distribution differed from the normal, and hence non-parametric tests were performed. Medians, average, 25 and 75% percentiles and minimum and maximum values of variables are presented. We used the Kruskal-Wallis ANOVA, Mann-Whitney U-test and multiple comparisons of mean rank tests to verify the significance of differences between the gas fluxes in different land use categories (N, D, A, M, P, and FM) and the Spearman Rank Correlation and non-linear regression, in order to analyse the relationship between GHG fluxes and environmental conditions (air and soil temperatures from different depths, water level depth, and chemical properties of peat (S) and water samples (Ca^{2+}, SO_4^{2-}) (III, IV). The statistical analysis was carried out using *Statistica 7.1* (StatSoft Inc.) and Microsoft Office Excel 2007 programs. The level of significance of $p \leq 0.05$ was accepted in all cases.

Additionally, redundancy analyses (RDA) were applied to relate gas emission data to environmental parameters (Legendre & Legendre, 1998) (III). The soil temperature and depth of groundwater data were used in RDA as explanatory variables, and the land use categories were considered to be a categorical value. A forward selection procedure with 1000 permutations was applied for the selection of statistically significant explanatory variables. For RDA, the CANOCO 4.52 program was used.

In terms of CO_2 emissions, we were unable to estimate NEE values, and thus soil heterotrophic respiration was measured. However, in active peat extraction sites as well as in abandoned sites with none or very sparse vegetation cover, the soil efflux values measured in chambers can be considered to be the NEE values for these sites. In *Phalaris* sites carbon balance was also estimated as plant biomass was measured.

2.2.5. Meteorological data

Meteorological analyses are based on air temperature, measured hourly and calculated daily, as well as daily, monthly and annual precipitation as recorded at the Meteorology Station of Tartu Observatory (N58º 15’55’’, E26º27’58’’), corresponding to the weather conditions at the Sangla study site (16 km from the station); from Viljandi Meteorology Station (N58° 22´40´´, E25°36´01´´), corresponding to the Soomaa study sites (25 km from the station), and at Jõhvi Meteorology Station (N59°19´44´´, E27°23´54´´), corresponding to the Hiiesoo (17 km from the station), Puhatu (16 km from the station) and Kasesoo (25 km from the station) study sites; and from Pärnu Meteorology Station (N 58°25´11´´, E 24°28´11´´), corresponding to the Lavassaare site (20 km from the station) (Fig. 2). The period from 1980 to 2010 was analysed on the basis of the information from Viljandi, Tartu and Jõhvi stations – the mean air temperature during the vegetation period varied from 10.1 to 13.1 C^{o} in Tartu and Viljandi, and was lower in eastern Estonia (9.5 to 12.5C^{o}). In 2009 annual mean air temperatures were slightly higher (0.2–0.3C^{o}), and dropped in 2010 (0.5–0.6C^{o}) compared to the 30-year average at all weather stations; temperatures in the vegetation period were similar in 2009 (only 0.1C^{o} higher in Tartu), but were significantly higher in 2010 – 1–1.2^{o}C. Annual precipitation varied from 414 to 1001 mm during the period from 1980 to 2010, and in 2009 these were significantly higher in all areas (71–154 mm), but in 2010 only in Tartu and Viljandi (185 and 63 mm respectively).

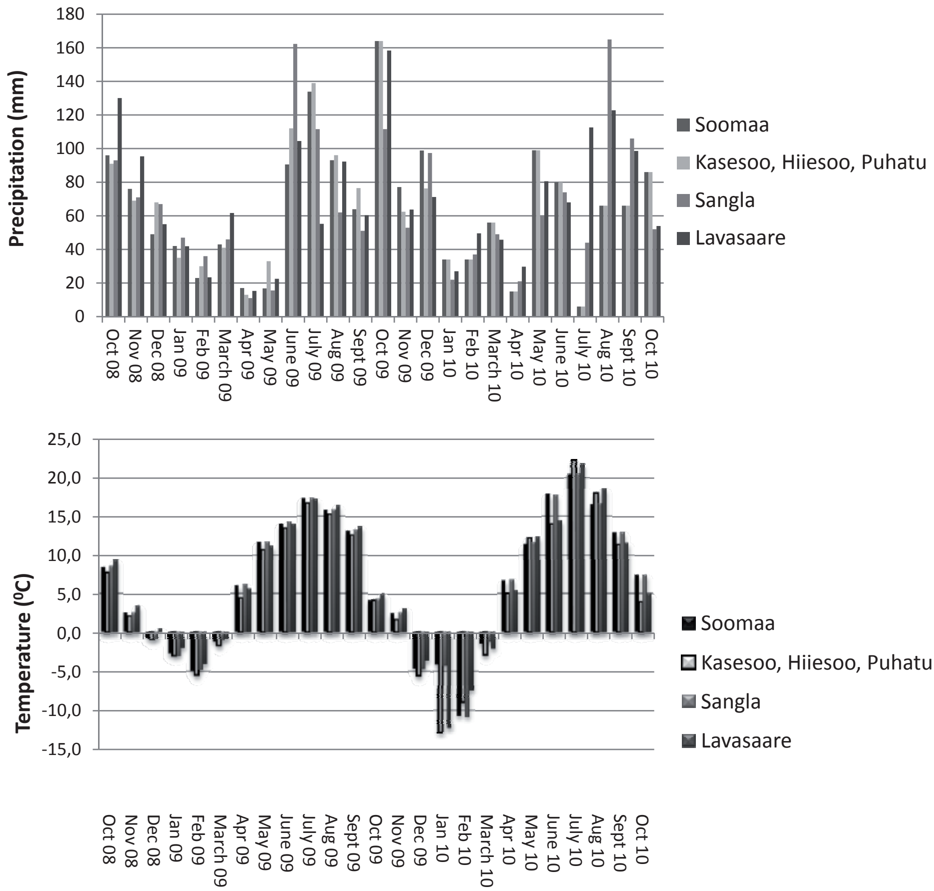


Figure 2. Mean monthly precipitation and air temperature in 2009 and 2010 at Viljandi weather station (corresponding to the study sites in Soomaa), Jõhvi weather station (corresponding to the study sites in Kasesoo, Hiiesoo and Puhatu), Tartu weather station (corresponding to the study site in Sangla) and Pärnu weather station (corresponding to the study site in Lavassaare).

3. RESULTS

3.1. Literature study

The literature study (I) indicates that compared to CO_2 sequestration in non-altered peatlands, drainage and lowered water level lead to a significant increase in CO_2 emissions in all peatland types. Emissions from drained ombrotrophic bogs were significantly lower than from other peatlands, which could be explained by lower rates of elemental cycling in nutrient-poor habitats (see also Alm *et al.*, 2007). Estimates of forest C sequestration capability (according to Estonian conditions) were combined with studies of emission rates, but these data did not lead to the conclusion that forestry drained areas are net sinks of C.

Methane emissions are lower in drained as opposed to undrained mires, and greater in nutrient rich minerotrophic and transitional fens as opposed to ombrotrophic bogs. There are fewer data on N_2O emissions, but these indicate a significant increase in gas emissions with drainage, especially in forestry drained areas. In pristine, nutrient poor ombrotrophic bogs, N_2O emission has been estimated to be small and inconsequential.

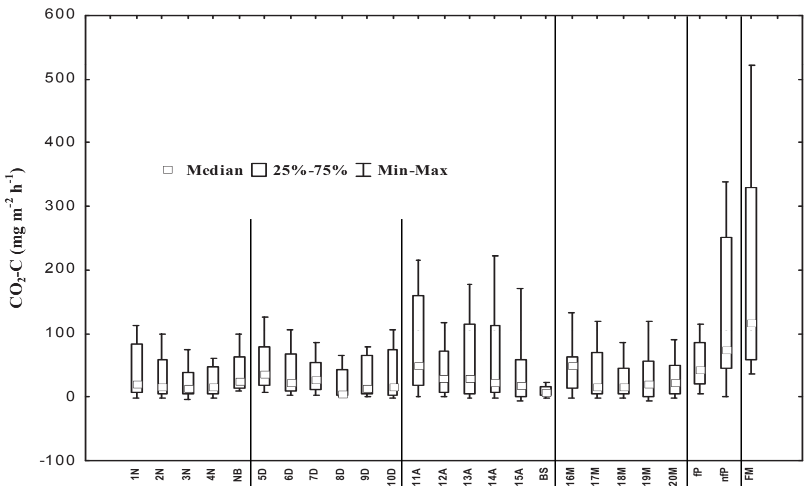
3.2. Soil greenhouse gas CO_2, CH_4 and N_2O emissions from study sites

3.2.1. Soil CO_2 flux

The averaged soil efflux of carbon dioxide varied between –5.58 and 521.95 mg CO_2-C m^{-2} h^{-1}. Low or negative CO_2 efflux values were registered in the winter period (November-March), when measurements were taken at temperatures below 0^o C. Emissions during the vegetation period (April to September 2009) provided 89% of all fluxes, but were lowest in site category A (67%), and in other categories (N, D, M) emissions ranged from 85–90%.

There was a significant difference between the emissions of two categories grouped as N, D, A, M and P, FM (Kruskal-Wallis ANOVA test, multiple comparison of mean ranks test), median values of CO_2-C fluxes were similar in natural, drained, and active peat extraction areas; emissions were higher in site category A and increased even further at P and FM (Fig. 3).

Emissions from all areas correlated with soil temperature measured from different (0, 10, 20, 30, and 40 cm) depths (Spearman rank correlation coefficient $\rho = 0.80$; $p < 0.05$). The strongest correlation was in areas with high water level – R^2 value of 0.64 ($p < 0.05$) (areas in Soomaa), and lower in peat extraction areas – R^2 value of 0.54 ($p < 0.05$). As the results of the analysis did not show a significant difference between emissions according to temperatures at different depths – R^2 value was 0.48 to 0.60 ($p < 0.05$), data is combined into one figure (Fig. 4).



N – Natural; a	D – Drained; a	A – Abandoned;a	M – Mined; a	P ; b	FM ,b
17.9 (31.9); 8.2-50.3	21.9 (34.0); 6.4-58.9	21.3 (51.4); 6.5-83.3	19.9 (34.1); 4.9-55.8	*	**

* **P – *Phalaris*** 59.3 (92.8); 27.2-104.7
** **FM– Fen meadow** 117.71 (197.8) 63.2-323.1

Figure 3. Soil efflux of CO_2-C from natural (N), drained (D), abandoned (A), active (mined) peat extraction (M) sites, *Phalaris* (P) site and fen meadow (FM). Given values: median, average (in brackets), and interquartile range (mg C m^{-2} h^{-1}). A and b – significantly differing values (Kruskal-Wallis ANOVA test and multiple comparison of mean ranks test).

1N, 2N – Valgeraba mire, pristine bog belonging to the wooded hummock bog subtype, gas emissions were measured from the hummock micro site and from level patches between plenty of hummocks, vegetation: *Calluna vulgaris, Empetrum nigrum, Andromeda polifolia, Oxycoccus palustris, Pinus sylvestris,* and different *Sphagnum* species
3N – Kuresoo mire, hollow-ridge bog subtype and an undisturbed area, gas emissions were measured from a hollow. Typical plants: *Sphagnum* species. vegetation: *Drosera anglica, Rhynchospora alba* and *Scheuchzeria palustris* and different *Sphagnum* species
4N – Kuresoo mire, 20 meters range from the site 3N, gas emissions were measured from hummocks, vegetation: *Calluna vulgaris, Empetrum nigrum, Polytrichum strictum,* and *Sphagnum* species
NB – Maima mire, natural raised bog, chambers were installed on *Calluna vulgaris*-*Ledum palustre*-hummocks and two on hollow sites (*Eriophorum vaginatum* and *Sphagnum* species)
5D – Kasesoo mire, wooded hummock bog subtype group affected by drainage, vegetation: *Pinus sylvestris, Betula pubescens, Andromeda polifolia, Calluna vulgaris, Chamaedaphne calyculata, Eriophorum vaginatum, Oxycoccus palustris, Empetrum nigrum, Drosera rotundifolia,* and *Sphagnum* species
6D, 7D – Valgeraba mire, mesotrophic (mixotrophic) bog forest site type drained for forestry, vegetation: *Pinus sylvestris, Betula pubescens, Calluna vulgaris, Melampyrum pratense, Vaccinium uliginosum, Rubus chamaemorus, Polytrichum strictum,* and different *Sphagnum* species
8D – Kuresoo mire, same habitat as 3N and 4N but the area is under a strong drainage influence, gas emissions measured from hollow, vegetation: *Rhynchospora alba*
9D – Kuresoo mire, same habitat as 3N and 4N but the area is under a strong drainage influence, gas emissions measured from hummocks, vegetation: *Calluna vulgaris* and *Empetrum nigrum*, and lichens (*Cladonia* species)
10D – Kuresoo mire, same habitat as 9D, gas emissions measured from hummocks consisting mainly of *Eriophorum Vaginatum*
11A – Sangla peat extraction area, site belongs to mesotrophic (mixotrophic) bog forest site type and is under a strong drainage influence, vegetation: *Betula sp.*, *Pinus sylvestris*, *Populus tremula*, *Frangula alnus, Fragaria vesca, Rubus idaeus,* and *Molina caerulea*
12A – Kasesoo mire, an area abandoned for 20 years, vegetation: sparsely covered with trees a few meters high (*Betula pubescens, Pinus sylvestris*) and *Calluna vulgaris*, vegetation removed 2nd part of measurement period
13A – Puhatu mire, Oru peat extraction area, inactive peat extraction area that has not been used for 5 years, vegetation: *Calamagrostis epigeios* and *Calamagrostis neglecta*
14A – Hiiesoo mire, site has been unused for 10 years, vegetation: *Calamagrostis epigeios*, and some *Eriophorum vaginatum*
15A – Hiiesoo mire, site has been unused for 25 year, bare peat surrounded by rare vegetation: *Betula pubescens, Pinus sylvestris, Calluna vulgaris, Tussilago farfara, Juncus articulatus* and *Carex flava*
BS – Lavassaare peat extraction area, site has been unused for 5 years, no vegetation
16M – Kasesoo mire, an active peat extraction area, no vegetation
17M – Puhatu mire, an active peat extraction area, no vegetation
18M – Puhatu mire, an active peat extraction area, no vegetation
19M – Hiiesoo mire, an active peat extraction area, no vegetation
20M – Hiiesoo mire, an active peat extraction area, no vegetation
fP – Lavassaare peat extraction area, fertilized *Phalaris* cultivation
nfP – Lavassaare peat extraction area, nonfertilized *Phalaris* cultivation
FM – Lavassaare, fen meadow outside of peat extraction area located, vegetation: *Elytrigia repens, Urtica dioica*

Nevertheless, higher correlations were detected at depths of 10 and 20 cm. RDA analysis indicated that water level and soil temperature at 10 cm from the ground surface explained 68.9% of CO_2-C fluxes (III).

The median values of cumulative annual soil effluxes of CO_2-C from natural, drained, abandoned, active extraction, *Phalaris*, and fen meadow sites were 1563 (ranging from 1167 to 2127), 1921 (507–3276), 1863 (683–4322), 1741 (1363–4382), 4783 (3583–5983), and 11,353 kg CO_2-C ha^{-1} y^{-1} respectively.

In comparison with emissions during the vegetation period in 2009 and 2010, there were significantly higher fluxes from sites 4N, 9D, and 10 D (Table 2). Weather conditions were warmer in 2009 (Fig. 2), and this is also reflected in soil temperatures – the Mann-Whitney U test does not show a statistically significant difference comparing emissions from different years, but there is a statistically significant difference in average temperatures (soil temperatures from different depths and aboveground temperatures).

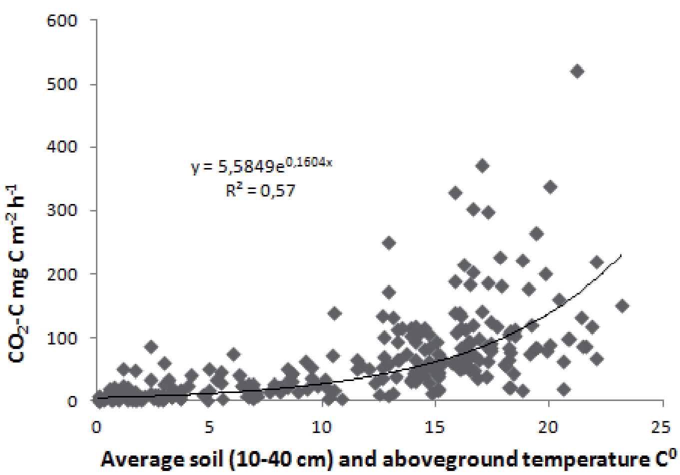


Figure 4. The relationship between CO_2-C efflux and average (+/– standard deviation) soil (in 10, 20, 30 and 40 cm) and aboveground air temperatures from all study sites.

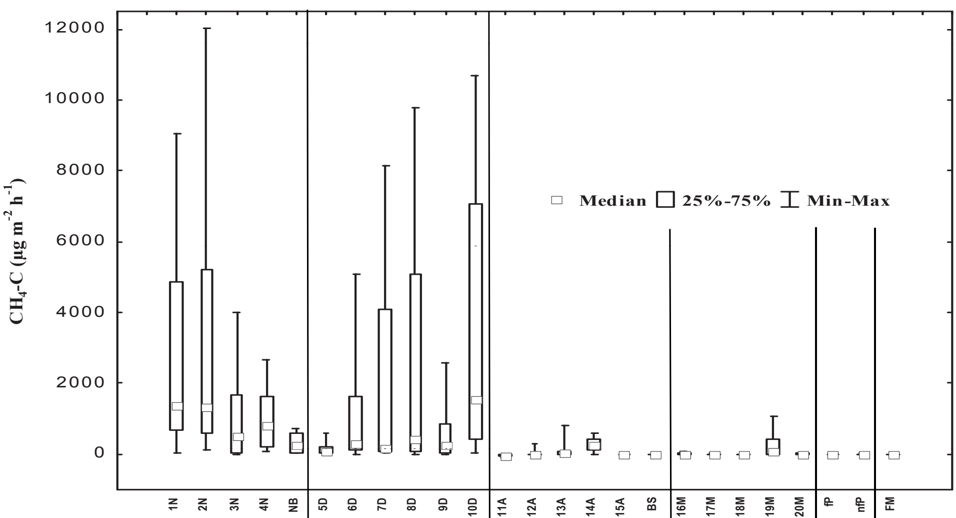
Table 2. Comparison of GHG emissions during vegetation period in 2009 and 2010 from sites in Kuresoo raised bog: 8D, 9D, 10D, 3N, 4N, and in Sangla peat extraction area (11A). For the abbreviations of site types see Fig. 3.

Site	**8D**		**9D**		**10D**		**3N**		**4N**		**11A**	
Year/gas	2009	2010	2009	2010	2009	2010	2009	2010	2009	2010	2009	2010
CO_2-C mg C m^{-2} h^{-1}												
A	4.74	33.57	9.32	33.30	7.23	16.20	9.48	27.27	15.48	16.24	22.43	0.91
M	20.65	44.65	19.21	93.26	38.93	139.88	22.71	37.20	21.57	85.25	64.14	27.25
J	33.71	75.23	58.82	183.01	75.27	142.52	29.11	68.00	44.36	113.53	133.22	131.35
J	65.44	68.71	78.03	131.88	92.32	150.40	74.11	64.24	49.49	87.55	186.77	114.00
A	53.32	18.63	71.92	108.06	106.79	104.56	50.57	22.63	61.07	57.82	215.65	265.21
S	51.24	9.23	70.18	54.63	74.59	74.60	46.64	11.39	50.79	30.07	188.24	227.25
O	6.85	4.63	27.81	9.91	27.40	17.00	3.90	5.01	15.05	10.43	78.69	115.77
average	**33.71**	**36.38**	**47.90**	**87.72**	**60.36**	**92.17**	**33.79**	**33.68**	**36.83**	**57.27**	**127.02**	**125.96**
CH_4-C µg m^{-2} h^{-1}												
A	175.23	72.56042	43.27	1264.21	476.63	616.6881	51.11	116.40	239.82	201.04	–14.51	–29.85
M	197.47	556.5855	196.02	938.84	1316.29	6843.503	677.06	1258.57	188.72	437.82	–66.37	–65.20
J	4984.17	4287.92	818.52	7131.85	5146.87	16394.44	989.37	2373.64	2674.77	1197.65	–62.70	–63.80
J	9774.33	4460.17	1423.47	5584.83	8966.83	7439.28	2345.89	3547.87	924.15	3155.05	–78.89	–74.21
A	5316.10	3636.29	879.80	4848.73	10698.48	6733.16	2946.12	3392.03	1403.03	2611.00	–81.99	–77.30
S	5178.36	2934.73	2580.10	7128.63	10629.27	12201.57	4002.37	4787.44	2521.35	1066.45	–27.19	–58.58
O	2967.26	333.93	214.11	100.97	1813.86	3600.801	331.96	380.69	719.15	1357.01		
average	**4084.70**	**2326.03**	**879.33**	**3856.87**	**5578.32**	**7689.92**	**1620.55**	**2265.23**	**1238.71**	**1432.29**	**–55.27**	**–61.49**
N_2O-N µg m^{-2} h^{-1}												
A	–0.77	–2.09	0.53	–1.87	3.02	2.85	–2.20	–1.20	2.50	–0.76	56.65	46.18
M	–0.45	1.61	0.10	2.64	0.08	1.64	–0.34	–1.75	–1.98	–0.97	13.12	20.41
J	–0.62	–1.89	–2.13	3.94	0.17	10.20	–0.76	–0.57	–0.55	–1.74	13.59	1.72
J	–3.16	17.11	–2.98	–2.12	2.79	0.68	–0.06	–1.36	–0.18	–1.71	15.22	7.74
A	–1.01	0.38	5.18	3.39	35.31	–2.64	–1.60	1.67	–0.84	1.81	11.16	7.04
S	0.04	–1.62	2.62	–2.38	–6.99	–2.02	–1.17	0.27	–0.97	–3.27	2.44	2.00
O	0.05	0.01	0.77	0.59	–0.62	0.15	0.95	–1.09	–0.32	1.18	0.00	
average	**–0.85**	**1.93**	**0.58**	**0.60**	**4.82**	**1.55**	**–0.74**	**–0.57**	**–0.33**	**–0.78**	**16.03**	**14.18**

3.2.2. Soil CH_4 flux

The averaged soil efflux of methane varied between –81.98 and 16,687.63 µg CH_4-C m^{-2} h^{-1}. Low or negative CH_4 emission values were registered in the winter period (November-March), when measurements were taken at temperatures below 5°C. Emissions during the vegetation period (April to September 2009) provided 82% of all fluxes, while it was lowest in site category A (67%), and in other categories (N, D, M) the range was from 78–84%.

There were two groups with significant difference between emissions – between N, D and A, M, P, FM) (Kruskal-Wallis ANOVA test, multiple comparison of mean ranks test), while median values of CH_4-C fluxes were highest in natural and drained areas and diminished severely in peat extraction areas; at site FM the emissions were negative (Fig. 5).



N – Natural; a	D – Drained; a	A – Abandoned;b	M – Mined; b	P ; b	FM , b
812.0 (1838.2); 71.1–2370.5	270.1 (1630.0); 73.2 – 1691.0	0.7 (61.7); -9.3–28.3	1.3 (57.4); -0.5–25.3	*	**

•***P – Phalaris*** 2.4 (4.2); 1.1-5.2
** **FM – fen meadow** -11.7 (-11.8); -7.6- -1.2

Figure 5. CH_4-C emissions from natural (N), drained (D), abandoned (A), active (mined) peat extraction (M) sites, *Phalaris* (P) sites, and the fen meadow (FM). Given values: median, average (in brackets), and interquartile range (µg C m^{-2} h^{-1}). A and b – significantly differing values (Kruskal-Wallis ANOVA test and multiple comparison of mean ranks test). For the abbreviations of site types, see Fig. 3.

Emissions correlated negatively with water level depth (ρ = –0.60), and there was also a significant correlation at soil temperatures above 10°C (Fig. 6). Emissions increased significantly at water table levels above 30 cm (Fig. 7). In addition, a weak but significant correlation was found between CH_4 emission and soil temperature measured from different depths and aboveground air temperature (ρ = 0.20–0.27; $p < 0.05$). In analyzing areas with a high water table (1N, 2N, 3N, 4N, NB, 5D, 6D, 7D, 8D, 9D, 10D, see also Table 1), a strong correlation was found (ρ = 0.65; $p < 0.05$) between CH_4 emissions and temperatures (III). In this respect, the correlation was not significant in other study sites with an average low water table, even though in some areas under strong drainage influence it fluctuated up to the surface. RDA analysis showed that CH_4-C emissions are well explained by site type (48.9%), and to a lesser extent by environmental variables (36.1%) (III).

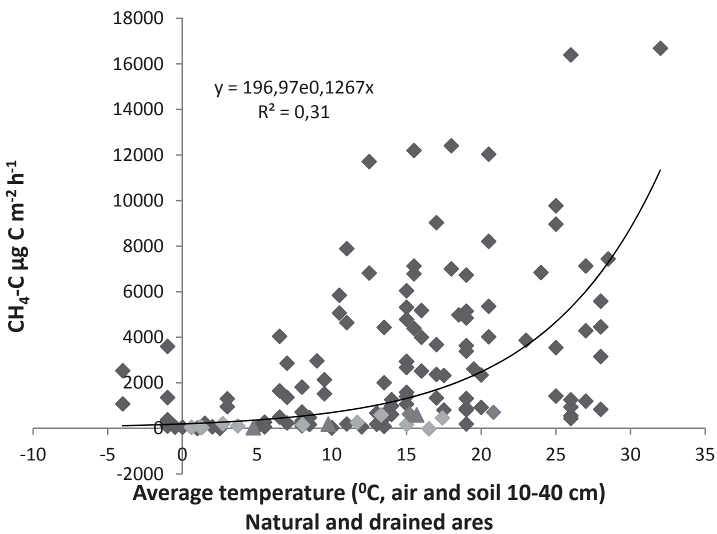


Figure 6. The relationship between CH_4-C emission (µg C m^{-2} h^{-1}) and average (+/– standard deviation) soil temperatures (10, 20, 30 and 40 cm) and aboveground air temperature from all study sites with a high water table (1N, 2N, 3N, 4N, NB,5D, 6D, 7D, 8D, 9D, 10D).

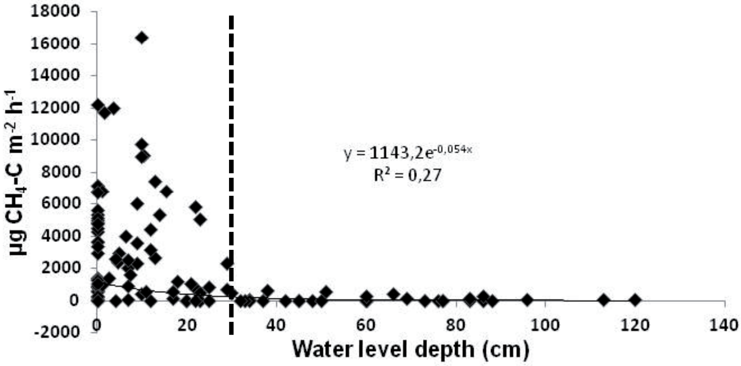


Figure 7. The relationship between CH_4-C emission (µg C m^{-2} h^{-1}) and water level depth (cm) for all study sites at average soil temperature values above 10° C. Emissions increase at water table levels above 30 cm.

The median values of cumulative annual soil effluxes of CH_4-C from natural, drained, abandoned, active extraction, *Phalaris*, and fen meadow sites were 71.1 (ranging from 23.9 to 120.8), 23.7 (8.1 – 137.1), 0.06 (–4.8 – 20.4), 0.12 (–0.1 – 6.1), 0.30 (0.20 – 0.31), and –1.23 kg CH_4-C ha^{-1} y^{-1} respectively.

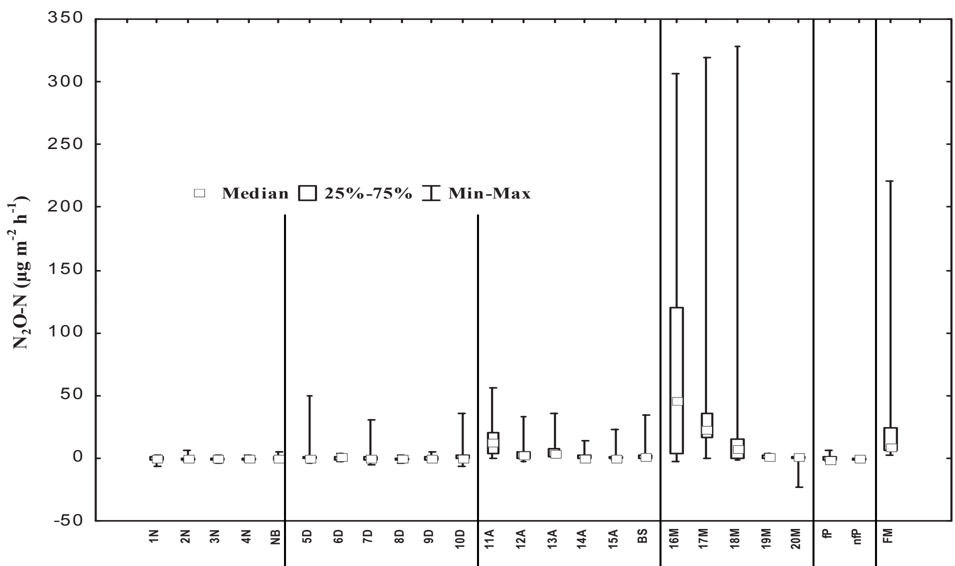
In comparing emissions during the vegetation period in 2009 and 2010, there were higher fluxes from all sites other than 8D and 11A (Table 2). Weather conditions were warmer in 2009, and this is also reflected in soil temperatures. The Mann-Whitney U test does not show a statistically significant difference in the comparison of emissions from different years.

3.2.3. Soil N_2O flux

Average emissions of N_2O-N varied between –22.71 and 328.8 µg N_2O-N m^{-2} h^{-1} (Fig. 8), and many samples were close to the detection limit of the gas chromatograph. There was a significant difference between all site categories N, D, P and A, M, FM (Kruskal-Wallis ANOVA test, multiple comparison of mean ranks test); the highest emissions were measured from active peat extraction sites (Fig. 8). It was noticed that the average high annual emissions rates are determined by sporadic peaks. A significant correlation between surface temperature and N_2O flux on the fertilized *Phalaris* site (fP) and in the FM were also registered. A slight but insignificant negative relation was also found between the C : N ratio in peat and N_2O flux. Significantly higher values were registered from 3 active peat extraction areas (16M, 17M, 18M), from an area severely affected by peat mining (11A), and from the fen meadow (FM). Emissions correlated negatively with water level depth ($\rho = -0.35$; $p < 0.05$), but not with soil temperature measured from different depths. RDA analysis showed that N_2O emissions are explained by environmental variables (22.1%) and to a lesser extent by site type (10.0%) (III).

In comparison with emissions during the vegetation period in 2009 and 2010, the Mann-Whitney U test does not show a statistically significant difference when one compares emissions from Kuresoo mire in different years.

The median values of cumulative annual soil effluxes of N_2O-N from natural, drained, abandoned, active extraction, *Phalaris*, and fen meadow sites were –0.05 (ranging from –0.06 to 0), –0.01 (–0.06–0.06), 0.17 (0.02–1.06), 0.19 (0.06–3.97), –0.05 (–0.09–0.02), and 2.64 kg N_2O-N ha^{-1} y^{-1} respectively.



N – Natural; a	D – Drained; a	A – Abandoned;b	M – Mined; b	P; a	FM; b
-0.6 (-0.4); -1.3–0.6	0.1 (1.4); -1.0–0.9	2.0 (6.1); 0.0–6.2	2.2 (33.4); 0.2–22.5	*	**

* **P – *Phalaris*** -0.7 (-0.4); -1.7–0.4
** **FM – Fen meadow** 9.1 (32.6); 6.9–22.2

Figure 8. N_2O-N emissions from natural, drained, abandoned and active (mined) peat extraction sites. Given values: median, average (in brackets) and interquartile range (µg N m^{-2} h^{-1}). A and b – significantly differing values (Kruskal-Wallis ANOVA test and multiple comparison of mean ranks test). For the abbreviations of site types see Fig 3.

3.4. Carbon sequestration by reed canary grass

The net primary production (NPP) of aboveground plant biomass was 3913 and 6928 kg C ha^{-1} yr^{-1} for non-fertilized and fertilized *Phalaris* sites (nfP, fP) respectively, whereas the respective belowground NPP are 5750 and 6879 kg C ha^{-1} yr^{-1}. In considering both soil and root respiration (CO_2 emission) data and aboveground and biomass data, the carbon balance of nonfertilized and fertilized *Phalaris* sites (nfP, fP) was calculated to be –6082 and –7818 kg C ha^{-1} yr^{-1} (IV). Therefore the areas acted as a sink for carbon.

4. DISCUSSION

4.1. Soil CO_2 flux and C balance

The results of the field work correspond to other studies in which CO_2 emissions are strongly correlated with soil temperatures (e.g. Waddington *et al*., 2001; Koh *et al*., 2009; Shurpali *et al*., 2008; Ojanen *et al*., 2010) (Fig. 4, III, IV). No significant correlation was found between CO_2 flux and water level, which was significantly lower in peat extraction areas, and the fluctuation of the water table had a greater amplitude than in natural areas and sites under category D. Nevertheless, the RDA analyses indicated that water level and soil temperature at 10 cm explain 67% of the CO_2-C flux (III). Also, it was detected that higher precipitation level, snow melt water and the subsequent rise in water level caused a reduction in CO_2 emissions (IV). However, a comparison of the measurements in two consecutive years in Kuresoo did not support the immediate relationship between increased temperatures (average temperature during the vegetation period and soil temperatures), slightly lowered water levels and CO_2 emissions, although one of the years was drier and warmer. Emissions increased in only three areas (4N, 9D, 10D) out of five. These three sites had denser vegetation cover and consisted of hummocks, and therefore changes in emissions could also be explained by shifting (fresh) litter availability and input and soil humidity. Two other areas were less vegetated – drained (8D) and natural (3N) hollows have more potential for decreasing soil humidity at the soil surface level than hummocks – and excessive dryness on the soil surface could limit the temperature response for peat respiration on the upper (0–3 cm) layer, as shown by Mäkiranta *et al.* (2010).

Emissions from natural (N) and drained areas (D) did not differ significantly with areas affected by peat extraction (A; M), which supports the finding that low substrate quality recalcitrant well-decomposed peat (Basiliko *et al.*, 2007) and the absence of fresh litter could cause lower emissions from bare peat sites (Waddington *et al.,* 2001). In addition, bacterial population has been found to be lower in post-vacuum-extracted peatlands than in natural mires (Croft *et al.,* 2001), which could explain the lower CO_2 emissions from peat extraction areas. On the other hand, there were also lower emissions from drained areas (e.g. 8D) than from other sites of this type, such as peat extraction and natural sites. The site has sparse vegetation cover (*Rhynchospora alba*) and a lack of *Sphagnum* moss, showing the effect of drainage. The soil surface is open, with highly mineralized peat. Therefore unfavourable conditions for further peat mineralization have already developed, and low litter availability leads to low emissions.

The higher emissions from vegetated sites and lower fluxes from bare peat sites in abandoned and active peat extraction areas were probably related to the presence of plants and the availability of fresh litter (e.g. the high emissions from *Phalaris* plots due to the formation of fresh litter with easily decayable C

(IV)), the inhibited mineralization of bare peat and consequences arising from the removal of the upper peat layers and the exposure of well composed (III) (see also Basiliko *et al.,* 2007) and low substrate quality recalcitrant peat (Waddington *et al.,* 2001). Nevertheless, in vegetated areas it is difficult to predict the proportion of CO_2-C originating from fresh litter and the decomposition of peat layers (Starkova *et al*., 2010).

Emissions from abandoned and active peat extraction ranged from 683 to 4322 and 1363 to 4382 kg CO_2-C ha^{-1} yr^{-1} (median values) (III, IV). The highest annual emission was determined from study site 11A, which is afforested and under a strong drainage influence. The other abandoned mining areas are either without vegetation (e.g. BS) and have significantly lower emissions, or have sparse vegetation. There was one active mining area with higher emissions (16M) which had been abandoned from peat extraction for 20 years, and field measurements were carried out just after site preparation – the removal of plants, trees and roots and the opening of the surface with less composed peat covered with fresh litter left from site preparation, which could be the cause of the higher emissions (III). There were no significant differences between sites in comparison of decomposition of the upper peat layer (0–50 cm). Rather there were similar emissions within the mires under extraction (areas 17M & 18M and 19M & 20M).

Active mining areas do not sequester C due to the absence of vegetation, and vegetation is either sparse or absent also on abandoned peat extraction sites. Therefore the global warming potential (GWP) of these areas is calculated on the basis of the emission measurements from field studies. The estimated rate of GWP for CO_2 is 6830 and 6383 kg CO_2 eq. ha^{-1} y^{-1} from abandoned and active peat extraction areas respectively. CH_4-C emissions provide 2 and 4, and N_2O-N 79 and 88 kg CO_2 eq ha^{-1} y^{-1} from abandoned and active peat extraction areas respectively. In comparing CO_2-C, CH_4-C, N_2O-N emissions calculated as kg CO_2 eq ha^{-1} y^{-1} , CO_2-C contributes most, i.e. 99% respectively. Thus as a result of mining activities these areas are neither accumulating nor storing carbon – a property which is also determined as ecosystems services of peatlands and mires (II). Gorham (1995) has estimated the rate of C storage in undrained peatlands to be 23 g C m^{-2} yr^{-1} (230 kg C ha^{-1} yr^{-1}); due to peat mining this property has declined in the areas under mining operations at a rate of 6657 t C yr^{-1} or 24,405 t CO_2 yr^{-1}. According to areal estimates – 19,574 active and 9371 ha abandoned peat mining areas (Ramst & Orru, 2009) – the global warming potential of these areas are 126,738 and 64,761 t CO_2 eq y^{-1}, in total 191,499 t CO_2 eq y^{-1}.

Our results are in the same range as other measurements in peat extraction sites – Sundh *et al*. (2000) in Sweden has estimated the total emissions during the growing season to be from 628 to 2787 kg CO_2-C ha^{-1} yr^{-1}. Shurpali *et al.* (2008) has reported emissions in two consecutive years to be 2640 and 4980 kg CO_2-C ha^{-1} yr^{-1}, whilst the lower emission was related to that year being drier. Based on GHG measurements, the 30-year monthly average air temperature and a simulation of temperature 5 cm belowground gave simulated annual emissions of 2672 kg CO_2-C ha^{-1} yr^{-1} in Finland (Alm *et al.*, 2007). This figure is also used for the National Inventory Report of GHGs in Finland (Greenhouse Gas Emissions in Finland 2011).

The emission rates from the *Phalaris* sites in our study (IV) – 3583 and 5983 kg CO_2-C ha^{-1} yr^{-1} (median values) also correspond to the results from the measurements performed in Finland by Shurpali *et al.* (2008), which were 3996 and 5368 kg CO_2-C ha^{-1} yr^{-1} in two consecutive years. In considering both soil and root respiration (CO_2 emission) data and aboveground and biomass data, the carbon balance of fertilized and nonfertilised *Phalaris* sites (fP, nfP) was –7818 and –6082 kg C ha^{-1} yr^{-1}. Thus abandoned peat extraction areas with bare peat generally act as C sources and *Phalaris* sites act as carbon sinks (IV).

There are several contradictory results regarding peat C balance in forestry managed peatlands, e.g. Lohila *et al.* (2007) have observed peat C loss on an afforested agricultural site 30 years after the establishment of the forest, whereas the C uptake of an afforested peatland was reported in Scotland (Hargreaves *et al.,* 2003). After drainage, the decomposition of organic matter increases and these sites may go from being carbon sinks to net sources of CO_2 (Mäkiranta *et al*., 2007; Maljanen *et al*., 2010). Several studies address the fact that the growing tree stand, its C sequestration and litter input plays an important role in compensating the increased organic matter decomposition rates that follow drainage (Mäkiranta *et al*., 2010). Nevertheless, there are only a few studies that have determined NEE for peatland ecosystems and in which measurements have included the canopy (Maljanen *et al*., 2010). Laurila *et al.* (2007) have reported in Finland a net annual CO_2 balance of –900 g CO_2 m^{-2} from minerotrophic site with Scots pines (*Pinus sylvestris*), measurements were performed using the Eddy Covariance method. Lohila *et al*. (2011) also report a significant CO_2 sink in a drained ombrotrophic treed peatland according to year-round NEE data – the annual NEE varied between –810 and –900 g CO_2 m^{-2}, whereas tree biomass (annual stem volume growth was 5.5 m^3 ha^{-1} yr^{-1} and the annual increment of live tree stand biomass 175 g C m^{-2} y^{-1}) explained only about 70% of the C sink. Therefore it was presumed that C is accumulated into the soil as dead organic matter. In order to estimate the impact of forestry drainage on GHG balances, however, the whole stand rotation must be included (Minkkinen *et al*., 2001).

In our study areas for forestry drainage (6D & 7D), emission rates were 1996 and 2436 kg CO_2-C ha^{-1} yr^{-1}. Annual stem volume growth was estimated at 4 m^3 ha^{-1} yr^{-1} (personal communication with the forest manager – State Forest Centre). Comparing these results with Lohila *et al*. (2011), there is a possibility that study sites are also net sinks of carbon.

Nonetheless, fluxes of CO_2, CH_4, and N_2O from boreal peatlands were estimated (I) based on the literature survey on soil GHG emission and net annual efflux measurements and C sequestration data in forests based on growth measurements of *Pinus Sylvestris* in Estonian transitional fens and ombrotrohic bogs. According to this data, the GHG balance for drained areas was positive, and thereof these areas were determined to be net sources of C and N.

In considering NEE and longer time periods, however, natural bogs and fens have acted as sinks for C and CO_2, which was also supported by the literature study (I). In the short term, the situation could shift from sink to source due to the drier climate and lower water table creating aerobic conditions favourable for the decomposition of organic matter (e.g. Bubier *et al*., 2003). Therefore the present data, which are based on GHG measurements from just one or two years, are too vague to offer a sufficient evaluation of the C balance in natural and afforested peatlands. In addition, analyses of net CO_2 exchange should incorporate peat loss due to wind and water erosion, which is estimated to take place at a rate of 6 mm y^{-1} in peat extraction areas (Waddington & McNeil, 2002). Measurements from ditches, which may contribute an additional 1–3% (Sundh *et al*., 2000; Schrier-Iijl *et al*., 2010), should also be included. In addition, life-cycle analyses of peat and timber use should be included in the further assessment of the C and CO_2 cycles of peatlands.

4.2. Soil CH_4 flux

High CH_4 emissions are common for natural areas and have been reported in several studies. In addition, ombrotrophic bogs have been found to have higher emissions than transitional fens (I). Areas with high water levels have greater potential for CH_4 production (Strack *et al*., 2003) and have a thinner aerobic zone suitable for methane oxidation (Lai, 2009). Our study shows that areas with severe changes in hydrological regime – peat extraction sites and fen meadow – also had low emissions (III, IV). In the case of groundwater deeper than 30 cm from the surface, no significant emissions appeared, a similar trend has been discovered by several investigations (e.g. Werner *et al.,* 2003; Soosaar *et al*., 2010). Nevertheless, in areas under drainage for forestry purposes, the ditches lost their capacity to lower the water level, and therefore the emissions were of a similar magnitude to natural areas (sites 6D, 7D).

In our study, a weak correlation was found with temperatures, especially in areas with lowered water tables – this attribute has also been found in other studies (e.g. Sundh *et al*., 2000). Sites with high water tables correlated better with temperatures (Fig. 6), corresponding to the results of Dinsmore *et al.* (2009). Nevertheless, in sites with two consecutive years of measurements, no enhancement of CH_4 emissions compared to higher temperatures and the slight reduction in water level were discovered. In case of hollows (e.g. 3N, 8D) the effect of drier climate followed by decreasing water level does not always cause changes of anaerobic conditions and potential for metanogenesis is retained (Frenzel & Karofeld, 2000).

The presence of *E. vaginatum* probably caused higher emissions in area 10D, with similar results reported in many studies (e.g. Minkkinen & Laine, 2006). The site was chosen to quantify the difference between areas with and without (9D) *E. vaginatum*, and the effect is significant (Fig. 5).

Data from the literature give an interquartile range for CH_4-C emissions from natural and drained transitional fens and ombrotrophic bogs of 15 to 75 and 7.5 to 15 kg CH_4-C ha^{-1} y^{-1} respectively (I). Although the emissions in this study fall within the range of emissions from natural areas (median values in range from 24 to 121 kg CH_4-C ha^{-1} y^{-1}), there is a difference in comparison with drained areas (except for 5D – 8.1 kg CH_4-C ha^{-1} y^{-1}) where the water level was relatively high (on average 15 cm below the ground surface). The most likely reason for this was the unexpectedly high water table identified at the drained sites in this study.

Our results confirm the significant reduction of emissions from peat excavation areas – median values of 0.12 (average 5.0) and 0.06 (average 5.2) kg CH_4-C ha^{-1} y^{-1} from active and abandoned peat mining areas respectively (III, IV). These are correlated with studies by Cleary *et al*. (2005) and Hyvönen *et al*. (2009), who have reported small CH_4-C fluxes from active peat extraction sites, i.e. 14.0 and 6.8 kg CH_4-C ha y^{-1} respectively. In addition, however, altered circumstances in peat mining areas do not necessarily result in the complete cessation of CH_4 emissions, as there are additional sources for emissions – for instance fluxes from drainage ditches (Sundh *et al*., 2000) and stockpiles (Alm *et al*., 2007).

A high S content was detected in *Phalaris* and FM sites, which is related to low CH_4 emissions from these areas (IV). The high S content in peat inhibits methanogenesis, as methanogenetic microorganisms are much weaker competitors for acetate and H_2 than sulphate-reducing bacteria (Deppe *et al.,* 2010).

Methane emissions were measured throughout the year and 82% was contributed during vegetation period which corresponds to results from Saarnio *et al.*(2007) – 85% and Nilsson *et al.* (2001) – 78%.

4.3. N_2O emission

As expected, there were small N_2O fluxes from natural areas, which is in accordance with the other research (Martikainen *et al*., 1995; Nykänen *et al.,* 1995*;* Regina *et al.*, 1996; Minkkinen *et al.*, 2002; Turunen *et al.*, 2002; Alm *et al.,* 2007; I). N_2O from the drained sites of this study was unexpectedly low, but this could be attributed to nutrient-poor habitats. The negative rates of N_2O fluxes show that in some soils of natural and drained area study sites, denitrification would be completed and resulted in N_2 emission. Nevertheless, the phenomenon of negative N_2O flux has not yet been clarified (Chapuis-Lardy *et al*., 2007). On the other hand, the negative and also small positive values measured in the study may be an error around zero. Therefore small values may also show an absence of either N_2O-N production or consumption. Similar conclusions have been reached by Hayden & Ross (2005) in estimating N_2O-N emission from an ombrotrophic peatland.

The highest fluxes were from sites 11A, 16M, 17M, and FM. All of these areas have a high C : N ratio. It has been shown that in organic soils, up to the C : N ratio of 25, the N_2O emissions decrease almost exponentially, and at higher values are almost nil (Klemedtsson *et al*., 2005). In the 11A, 16M, 17M, and FM, the average ratios of C : N were 17, 27, 24, and 15 respectively, which explain the high fluxes. At the same time, the BS site had a ratio of 22, but fluxes were slightly negative although the lack of vegetation could be favourable for higher emissions, as there is no competition for N by plants (Silvan *et al*., 2005). Measurements of N_2O-N emissions in this study are in the same range as results from peat mining areas in Finland, which were in the range of 0.03 to 0.12 kg N_2O-N ha^{-1} y^{-1} (Hyvönen *et al*., 2009). In addition, it is estimated that the majority of N_2O in peat harvesting areas is released from ditches and stockpiles (Alm *et al*., 2007). Alm *et al*. (2007) has reported 2.0 kg N_2O-N ha^{-1} y^{-1}, including ditch emissions.

CONCLUSIONS

The following conclusions can be drawn from this thesis:

I Peat mining alters the fluxes of CO_2, CH_4, and N_2O compared with those of natural peatlands;

II The median cumulative annual fluxes of CO_2-C, CH_4-C and N_2O-N in abandoned peat mining areas are 1863, 0.06 and 0.17 kg ha^{-1} y^{-1} respectively. The median cumulative annual fluxes of CO_2-C, CH_4-C and N_2O-N from active peat mining areas are 1741, 0.12 and 0.19 kg ha^{-1} y^{-1} respectively. These results also correspond to other emission rates determined from similar land use areas. Due to the lowered water table, the removed upper layer and sparse or absent vegetation, GHG emission in abandoned sites could remain similar to areas under peat extraction without restoration or other use (e.g. the cultivation of *Phalaris*) of these areas. Therefore abandoned and active mining sites are continuous net emitters of CO_2-C, CH_4-C and N_2O-N. According to areal estimates – 19,574 active and 9371 ha abandoned peat mining areas – the global warming potential of these areas are 126,738 and 64,761 t CO_2 eq y^{-1}, in total 191,499 t CO_2 eq y^{-1}. It is estimated that peat extraction has increased nearly ten-fold (from accumulation of 24,405 to emission of 191,499 t CO_2 eq yr^{-1}) the radiative forcing of areas under peat extraction related to emissions of GHGs.

III Emissions in natural and drained areas of this study did not differ significantly, although the vegetation confirmed the effects of drainage. This could be attributed to the water level, which was unexpectedly high in drained areas. Nevertheless, measurements from two consecutive years did not confirm a direct relationship with changes in emissions due to increasing temperatures and the slightly lowered water level. This confirms the need for long-term GHG measurements.

IV N_2O emissions from natural and drained areas were significantly lower than in peat extraction sites. This fact could be related to intensive peat mineralization due to lower water table, the C : N ratio in areas with high emissions, and also to the lack of vegetation – the main competitor for denitrifying microorganisms.

V Cultivation of *Phalaris* transforms abandoned peat extraction areas from net sources to net sinks of carbon. Nevertheless, use of *Phalaris* leads to high CO_2 fluxes compared to sites with bare peat or sparse vegetation. Therefore life cycle analyses are necessary in order to estimate the potential for mitigation of greenhouse gas emissions on abandoned peat extraction areas by growing *Phalaris*.

The results show that further studies should be undertaken in order to improve the estimation of the C balance of peatlands. These should include research on the ecosystem level and the estimation of net ecosystem emissions (NEE), and the life-cycle assessment of resources gained from peatlands (peat, timber, other biomass) should also be developed. Further analysis of microbial community composition may also be a main factor in explaining the variation in GHG emission between mire types and land use practices.

REFERENCES

Alm, J., Shurpali, N. J., Minkkinen, K., Aro, L., Hytönen, J., Laurila, T. 2007. Emission factors and their uncertainty for the exchange of CO_2, CH_4 and N_2O in Finnish managed peatlands. Boreal Environ. Res. 12: 191–209.

Basiliko, N., Blodau, C. P., Bengtson, P. C., Roehm, C., Moore, T. R. 2007. Regulation of decomposition and methane dynamics across natural, commercially mined, and restored northern peatlands. Ecosystems 10: 1148–1165.

Bridgham, S. D., Megonigal, J. P., Keller, J. K., Bliss, N. B., Trettin, C. 2006. The carbon balance of North American wetlands. Wetlands 26: 889–916.

Bubier, J. L., Bhatia, G., Moore, T. R., Roulet., N. T., Lafleur, P. M. 2003. Spatial and Temporal Variability in Growing-Season Net Ecosystem Carbon Dioxide Exchange at a Large Peatland in Ontario, Canada. Ecosystems 6: 353–367.

Chapuis-Lardy, L., Wrage, N., Metay, A., Chotte, J.-L., Bernoux, M. 2007. Soils, a sink for N_2O? A review. Glob. Change Biol. 13: 1–17.

Cleary, J., Roulet, N. T., Moore, T. R. 2005. Greenhouse gas emissions from Canadian peat extraction, 1990–2000: a life-cycle analysis. Ambio 34: 456–61.

Croft, M., Rochefort, L., Beauchamp, C. J. 2001. Vacuum-extraction of peatlands disturbs bacterial population and microbial biomass carbon. Appl. Soil Ecol. 18: 1–12.

Deppe, M., McKnight, D. M., Blodau, C. 2010. Effects of Short-Term Drying and Irrigation on Electron Flow in Mesocosms of a Northern Bog and an Alpine Fen. Environ. Sci. .Technol. 44: 80–86.

Dinsmore, K. J., Skiba, U. M., Billett, M. F., Rees, R. M. 2009. Effect of water table on greenhouse gas emissions from peatland mesocosms. Plant Soil 318: 229–242.

Frenzel, P., Karofeld, E. 2000. CH_4 emission from a hollw-ridge complex in a raised bog: the role of CH_4 production and oxidation. Biogeochemistry 51: 91–112.

Gorham, E. 1991. Northern peatlands: role in the carbon cycle and probable responses to climatic warming. Ecol. Appl. 1: 182–195.

Gorham, E. 1995. The biogeochemistry of northern peatlands and its possible response to global warming. In: Woodwell, G. M., Mackenzie, F. T. (Eds.) Biotic Feedbacks in the Global Climatic System: Will the Warming Feed the Warming? Oxford University Press, New York, pp 169–187.

Greenhouse Gas Emissions in Finland 1990–2009. National Inventory Report under the UNFCCC and the Kyoto Protocol. 2011. (viewed at 1.03.2012 http://www.stat.fi/tup/khkinv/fin_nir_20110415.pdf)

Hargreaves, K. J., Milne, R., Cannell, M. G. R. 2003. Carbon balance of afforested peatland in Scotland. Forestry 76: 299–317.

Hayden, M. J., Ross, D. S. 2005. Denitrification as a nitrogen removal mechanism in a Vermont peatland. J. Environ. Qual. 34: 2052–2061.

Hutchinson, G. L., Livingston, G. P. 1993. Use of chamber systems to measure trace gas fluxes. In: Harper, L. E., Mosier, A. R., Duxbury, J. M., Rolston, D. E. (Eds.). Agricultural Ecosystems Effects on Trace Gases and Global Climate Change. ASA Special Publication No. 55. American Society of Agronomy, Madison, MI, USA, pp. 1–55.

Hyvönen, N. P., Huttunen, J. T., Shurpali, N. J., Tavi, N. M., Repo, M. E., Martikainen, P. J. 2009. Fluxes of nitrous oxide and methane on an abandoned peat extraction site: Effect of reed canary grass cultivation. Bioresource Technol. 100: 4723–4730.

IPCC. 2007. Climate Change 2007: The Physical Science Basis. Cambridge University Press, Cambridge.
Janzen, H. H. 2004. Carbon cycling in earth systems – a soil science perspective. Agr. Ecosyst. Environ. 104: 399–417.
Järveoja, J., Laht, J., Maddison, M., Soosaar, K., Ostonen, I., Mander, Ü. 2012. Mitigation of greenhouse gas emissions on an abandoned peat extraction area by growing reed canary grass: Life-cycle assessment. Reg. Environ. Change (In press).
Karofeld, E., Ilomets, M. 2008. On the impact of oil shale mining and processing on mires in Northeast Estonia. International Mire Conservation Group. Newsletter 1:10–11.
Kimmel, K., Kull, A., Salm, J.-O., Mander, Ü. 2009. The status, conservation and sustainable use of Estonian wetlands. Wetlands Ecology and Management18 (4): 375–395.
Klemedtsson, L. K., Von Arnold, K., Weslien, P., Gundersen, P. 2005. Soil C:N ratio as a scalar parameter to predict nitrous oxide emissions. Global Change Biol. 11: 1142–1147.
Koh, H. S., Ochs, C. A., Yu, K. 2009. Hydrologic gradient and vegetation controls on CH_4 and CO_2 fluxes in a spring-fed forested wetland. Hydrobiologia 630: 271–286.
Lai, D. Y. F. 2009. Methane dynamics in northern peatlands: a review. Pedosphere 19: 409–421.
Laurila, T., Lohila, A., Aurela, M., Tuovinen, J.-P., Thum, T., Aro, L., Laine, J., Penttilä, T., Minnkinen, K., Riutta, T., Rinne, J., Pihlatie, M., Vesala, T. 2007. Ecosystem-level carbon sink measurements on forested peatlands. In: Greenhouse Impacts of the Use of Peat and Peatlands in Finland.Sarkkola, S. (Ed.). Ministry of Agriculture and Forestry, 11a/2007: 38–40.
Legendre, P., Legendre, L. 1998. Numerical Ecology, 2nd English ed Elsevier Science BV, Amsterdam, xv + 853 p.
Limpens, J., Berendse, F., Blodau, C., Canadell, J. G., Freeman, C., Holden J., Roulet, N., Rydin, H., Schaeoman-Strub, G. 2008. Peatlands and the carbon cycle: from local processes to global implications – a synthesis. Biogeosciences 5: 1475–1491.
Loftfield, N., Flessa, H., Augustin, J., Beese, F. 1997. Automated gas chromatographic system for rapid analysis of the atmospheric trace gases methane, carbon dioxide, and nitrous oxide. J. Environ. Qual. 26: 560–564.
Lohila, A., Laurila, T., Aro, L., Aurela, M., Tuovinen, J.-P., Laine, J., Kolari, P., Minkkinen, K. 2007. Carbon dioxide exchange above a 30-year-old Scots pine plantation established on organic-soil cropland. Boreal Environ. Res. 12: 141–157.
Lohila, A., Minkkinen, K., Aurela, M., Tuovinen, J. P., Penttila, T., Ojanen, P., Laurila, T. 2011. Greenhouse gas flux measurements in a forestry-drained peatland indicate a large carbon sink. Biogeosciences 8 (11): 3203–3218.
Maljanen, M., Sugurdsson, B. D., Guðmundsson, J., Óskarsson, H., Huttunen, J. T., Martikainen, P. J. 2010. Greenhouse gas balances of managed peatlands in the Nordic countries – present knowledge and gaps. Biogeosciences 7: 2711–2738.
Mander, Ü., Järveoja, J., Maddison, M., Soosaar, K., Aavola, R., Ostonen, I., Salm, J.-O. 2012. Reed canary grass cultivation mitigates greenhouse gas emissions from abandoned peat extraction areas. Glob. Change Biol. Bioenergy. DOI: 10.1111/j.1757-1707.2011.01138.x.
Martikainen, P. J., Nykänen, H., Alm, J., Silvola, J. 1995. Change in fluxes of carbon dioxide, methane and nitrous oxide due to forest drainage of mire sites of different trophy. Plant Soil 169(8): 571–577.

Minkkinen, K., Laine, J. 2006. Vegetation heterogeneity and ditches create spatial variability in methane fluxes from peatlands drained for forestry. Plant Soil 285: 289–304.
Minkkinen, K., Korhonen, R., Savolainen, I., Laine, J. 2002. Carbon balance and radiative forcing of Finnish peatlands 1900–2100 – the impact of forestry drainage. Glob. Change Biol. 8: 785–799.
Minkkinen, K., Penttilä, T., Hökka, H. 2001. Tree stand volume as a scalar for methane fluxes in forestry-drained peatlands in Finland. Boreal Environ. Res. 12: 127–132.
Mäkiranta, P., Hytönen, J., Aro, L., Maljanen, M., Pihlatie, M., Potila, H., Shurpali, N. J., Laine, J., Lohila, A., Martikainen, P. J., Minkkinen, K. 2007. Soil greenhouse gas emissions from afforested organic soil croplands and cutaway peatlands. Boreal Environ. Res. 12: 159–175.
Mäkiranta, P., Riutta, T., Penttilä, T., Minkkinen, K. 2010. Dynamics of net ecosystem CO_2 exchange and heterotrophic soil respiration following clearfelling in a drained peatland forest. Agr. Forest Meteorol. 150: 1585–1596.
Nilsson, M., Mikkelä, C., Sundh, I., Granberg, G., Svensson, B. H., Ranneby, B. 2001. Methane emission from Swedish mires: National and regional budgets and dependence on mire vegetation. J. Geophys. Res. 106 (D18): 20847–20860.
Nykänen, H., Silvola, J., Alm, J., Martikainen, P. J. 1995. Emissions of CH_4, CO_2 and N_2O from a virgin fen and a fen drained for grassland in Finland. J. Biogeogr. 22: 351–357.
Ojanen, P., Minkkinen, K., Alm, J. 2010. Soil–atmosphere CO_2, CH_4 and N_2O fluxes in boreal forestry-drained peatlands. Forest Ecol. Manag. 260: 411–421.
Paal, J., Ilomets, M., Fremstad, M., Moen, A., BØrset, E., Kuusemets, V., Truus, L., Leibak, E. 1999. Eesti märgalade inventeerimine 1997. a. Projekti „Eesti märgalade kaitse ja majandamise strateegia" aruanne. Eesti Loodusfoto, Tartu. *In Estonian.*
Paal, J., Leibak, E. 2011. Estonian Mires: Inventory of Habitats. Tartu.
Post, W. M., Emanuel, W. R., Zinke, P. J., Stangenbergen, A. G. 1982. Soil carbon pools and world life zones. Nature 298: 156–159.
Ramst, R., Orru, M. 2009. Eesti mahajäetud turbatootmisalade taastaimestumine. Eesti Põlevloodusvarad ja -jäätmed 1−2: 6−7. *In Estonian.*
Regina, K., Nykanen, H. Silvola, J., Martikainen, P. J. 1996. Fluxes of nitrous oxide from boreal peatlands as affected by peatland type, water table level and nitrification capacity. Biogeochemistry 35: 401–418.
Saarnio, S., Morero, M., Shurpali, N. J., Tuittila, E.-S., Mäkilä, M., Alm, J. 2007. Annual CO_2 and CH_4 fluxes of pristine boreal mires as a backround for the lifecycle analyses of peat energy. Boreal Environ. Res. 12: 101–113.
Salm, J.-O., Kimmel, K., Uri, V., Mander, Ü. 2009. Global warming potential of drained and undrained peatlands in Estonia: a synthesis. Wetlands 29(4): 1081–1092.
Salm, J.-O., Maddison, M., Tammik, S., Soosaar, K., Truu, J., Mander, Ü. 2012. Emissions of CO_2, CH_4 and N_2O from undisturbed, drained and mined peatlands in Estonia. Hydrobiologia. DOI: 10.1007/s10750-011-0934-7.
Schrier-Iijl, A. P., Kroon, P. S., Leffelaar, P. A., van Huissteden, J. C., Berendse, F., Veenendaal, E. M. 2010. Methane emissions in two drained peat agro-ecosystems with high and low agricultural intensity. Plant and Soil 329: 509–520.
Shurpali, N. J., Hyvönen, N. P., Huttunen, J. T., Biasi, C., Nykänen, H., Pekkarinen, N. 2008. Bare soil and reed canary grass ecosystem respiration in peat extraction sites in Eastern Finland. Tellus B. 60: 200–209.

Silvan, N., Tuittila, E. S., Kitunen, V., Vasander, H., Laine, J. 2005. Nitrate uptake by *Eriophorum vaginatum* controls N_2O production in a restored peatland. Soil Biol. Biochem. 37: 1519–1526.
Soosaar, K., Mander, Ü., Maddison, M., Kanal, A., Kull, A., Lõhmus, K., Truu, J., Augustin, J. 2011. Dynamics of gaseous nitrogen and carbon fluxes in riparian alder forests. Ecol. Eng. 37(1): 40–53.
Strakova, P., Anttila J., Spetz, P., Kitunen, V., Tapanila, T., Laiho, R. 2010. Litter quality and its response to water level drawdown in boreal peatlands at plant species and community level. Plant Soil 335: 501–520.
Strack, M., Waddington, J. M., Kellner, E., Price, J. S., Rochefort, L. 2003: Methane storage and emissions at a natural and drained fen in central Quebec. In: Järvet, A. & Lode, E. (Eds.) Proceedings of the International Conference on Ecohydrological Processes in Northern Wetlands. Tallinn, Estonia (June 30–July 03, 2003). Tartu University Press, Tallinn, Estonia, pp. 227–232.
Sundh, I., Nilsson, M., Mikkelä, C., Granberg, G., Svensson, B. H. 2000. Fluxes of methane and carbon dioxide on peat-mining areas in Sweden. Ambio 29 (8): 499–503.
Strakova, P., Anttila J., Spetz, P., Kitunen, V., Tapanila, T., Laiho, R. 2010. Litter quality and its response to water level drawdown in boreal peatlands at plant species and community level. Plant Soil 335: 501–520.
Turunen, J., Tomppo, E., Tolonen, K., Reinikainen, A. 2002. Estimating carbon accumulation rates of undrained mires in Finland—application to boreal and subarctic regions. Holocene 12: 69–80.
Waddington, J. M., McNeil, P. 2002. Peat oxidation in an abandoned cutover peatland. Can. J. Soil Sci. 82: 279–286.
Waddington, J. M., Rotenberg, P. A., Warren, F. J. 2001. Peat CO_2 production in a natural and cutover peatland: Implications for restoration. Biogeochemistry 54: 115–130.
Von Arnold, K., Hånell, B., Stendahl, J., Klemedtsson, L. 2005a. Greenhouse gas fluxes from drained organic forestsland in Sweden. Scand. J. Forest Res. 20: 400–411.
Von Arnold, K., Nilsson, M., Hånell, M., Weslien, P., Klemedtsson, L. 2005b. Fluxes of CO_2, CH_4 and N_2O from drained organic soils in deciduous forests. Soil Biol. Biochem. 37: 1059–1071.
Werner, C., Kenneth, D., Bakwin, P., Yi, C., Hurts, D., Lock, L. 2003. Regional-scale measurements of CH_4 exchange from a tall tower over a mixed temperate/boreal lowland and wetland forest. Glob. Change Biol. 9: 1251–1261.

SUMMARY IN ESTONIAN

Kasvuhoonegaaside CO_2, CH_4 ja N_2O vood soodes: kuivenduse ja maakasutuse muutuse mõju

Loodusliku sooökosüsteemi tähtsaim talituslik iseärasus on turba teke ja ladestumine (Paal *et al.,* 1999). Boreaalsed looduslikud sood akumuleerivad süsinikku ja lämmastikku ning mõjutavad kliimat globaalses ulatuses, sidudes CO_2 ja emiteerides atmosfääri CH_4 ning vähesel määral N_2O (Minkkinen *et al.*, 2002). Põhja laiuskraadidel paiknevatel turbaaladel on akumuleerunud hinnanguliselt 30% muldades paiknevast süsinikust (Gorham, 1991) ja talletunud biomassi ja pinnase orgaanilise ainena ligikaudu 20% maismaal paiknevatest süsiniku varudest (Post *et al.*, 1982; Janzen, 2004). Pikaajaline süsiniku akumuleerumine soodes toimub kiirusega 23 g C m^{-2} a^{-1} (Gorham, 1995), samas võivad sood olla lühiajaliselt ka süsiniku emiteerijad, näiteks kuivema ja soojema ilmastiku korral. Juhul, kui soode looduslik seisund muutub inimtegevuse või kliimamuutuste tõttu, muutub ka soode kasvuhoonegaaside bilanss. Eriti oluliseks teguriks CO_2 ja N_2O emissiooni suurenemisel on kuivendus (Martikanen *et al.*, 1995). Hinnanguliselt on Eestis rabade ja siirdesoode kuivendamise tagajärjel kasvuhoonegaaside CO_2, CH_4 ja N_2O summaarne emissioon CO_2 ekvivalentidesse ümberarvutatuna 2.3 kuni 2.7 korda suurem, kui see oleks looduslikus olekus soodest (Salm *et al.,* 2009).

Eesti soode kogupindala hinnatakse 240,000–245,000 ha ehk ligikaudu 5.5% territooriumist, seejuures on hinnatud nende pindala vähenemist viimase 60 aasta jooksul 2.6–2.8 korda (Paal & Leibak, 2011). Nende alade hulgas on ka ligikaudu 30,000 ha aktiivseid ja kasutusest väljajäänud turbakaevandusalasid (Ramst & Orru, 2009).

Kasvuhoonegaaside – süsinikdioksiidi (CO_2), metaani (CH_4) ning naerugaasi (N_2O) voogude mõõdistusandmed, mille põhjal on senini olnud võimalik hinnata Eesti siirdesoode ja rabade kasvuhoonegaaside voogusid, pärinevad vaid mõnedes riikides läbi viidud uuringutele (Soome, Rootsi, samuti Kanada ja Ameerika Ühendriigid), mis annavad teavet ühe ja harva rohkema järjestikuse aasta kohta. Et hinnata riigipõhiselt nende territooriumitel paiknevatel soode kasvuhoonegaaside bilanssi, on vajalik vastavate mõõdistuse läbiviimine, hõlmates uuringutega erinevad sootüübid ja vastavalt ka maakasutuse, oluline on ka nende pikemaealisus. Täiendavalt vajab hindamist ka turbaalade, sh soode süsinikubilanss, mis sisaldab endas lisaks kasvuhoonegaaside mõõtmisele ka turba, jääksoode võimaliku kasutusena näiteks päideroo (*Phalaris arundinacea* L.) ja turvasmuldadel raiutavast metsast saadud puidu kasutust käsitlevat elutsükli analüüsi.

Eesmärgiga hinnata kasvuhoonegaaside bilanssi Eesti soodes, alustati 2008. aasta juunis mõõtmisi Soomaa rahvuspargis: kuivendatud ja looduslikel aladel Kuresoos ja Valgerabas (9 mõõtmisala), alates 2008. a novembrist Tartumaal Sangla turbakaevandamisala kõrval paikneval kaevandamisest mõjutatud alal

(1 mõõtmisala) ja Kirde-Eestis Puhastu soostikus paiknevatel Oru turbaväljal ning Kasesoos kuivendusest mõjutatud soos ja kaevandamisaladel (6 mõõtmisala) ja Hiiesoo kaevandamisalal (4 mõõtmisala). 2010. a mais lisandusid välitööd Lavassaare ammendunud turbakaevandusaladel (5 mõõtmisala), kus põhitähelepanu pöörati päideroo istandusele, täiendavalt oli mõõtmisala mahajäetud kaevandusväljakul, siirdesoomullal paikneval heinamaal ning looduslikus soos. Kokku toimusid mõõtmised 25 alal. Kõikidel aladel toimusid mõõtmised vähemalt 12-kuulise perioodi jooksul, Soomaal ja Sanglas viidi mõõtmised läbi kahel aastal.

Gaasiemissioone mõõdeti suletud kambri meetodil. Proovide kogumiseks kasutati valgeid (vältimaks temperatuuri tõusu proovi kogumisel) ja läbipaistmatuid (vältimaks fotosünteesi) 65,5-liitriseid, umbes 50 cm diameetri ja kõrgusega PVC-kambreid. Päideroo kasvatamise aladel lisati taimestiku kõrguse kasvades 1.2 m kõrgused pikendused PVC kambritele. Mõõtmisel asetati kambrid varem maapinda paigaldatud, tasakaalustatud ja veega täidetud 0,2 m^2 pindalaga rõngastele.

Proovid koguti kõikidelt uurimisaladelt viielt rõngalt eelnevalt vaakumpumba abil õhust tühjendatud 100 ml klaaspudelitesse ühe tunni jooksul 30-minutilise intervalliga, s.t. kokku 15 proovi: igalt rõngalt kolm. Mõõtmisi viidi läbi kord kuus. Gaasiproovid analüüsiti Tartu Ülikooli Loodus- ja tehnoloogiateaduskonna geograafia osakonna laboris Shimadzu GC-2014 gaaskromatograafi süsteemi abil. Gaaside voog (µg või mg m^{-2} h^{-1}) pinna- ja ajaühiku kohta arvutati välja ühetunnise gaaside sisalduse muutuse järgi kambrites.

Proovivõtukohas mõõdeti põhjaveetaset, õhu ja pinnase temperatuuri (10, 20, 30 ja 40 cm sügavusel). Igalt turbakaevandusalal asuvalt uurimisalalt võeti lisaks pinnaseproov ning tehti selle keemiline ja mineraloogiline analüüs, lüsimeetritest kogutavate veeproovide järgi määrati süsiniku-, lämmastiku- ja fosforisisaldus. Kõigilt uurimisaladel määrati pinnase süsiniku ja lämmastiku sisaldus. Vastavad analüüsid teostati Tartu Keskkonnauuringute Keskuses. Välitingimustes mõõdeti veeproovide põhjal ka pH, redokspotentsiaal ja hapnikusisaldus.

CO_2-C emissioonid looduslikelt, kuivendatud, mahajäetud ja tegutsevatelt turbatootmisaladelt, päideroo kasvatusaladelt ja siirdesoomullal paiknevalt heinamaalt olid vastavalt 1563 (1167–2127), 1921 (507–3276), 1863 (683–4322), 1741 (1363–4382), 4783 (3583–5983) ja 11,353 kg CO_2-C ha^{-1} a^{-1} (esitatud mediaani väärtused ja vastava maakasutustüübi all olevate uurimisalade vastavate väärtuste ulatus).

CO_2-C emissioon seostus tugevalt pinnasetemperatuuridega, mida kinnitavad ka mitmete teiste mõõtmistulemuste andmed (näit. Waddington *et al.*, 2001; Koh *et al.*, 2009; Shurpali *et al.*, 2008; Ojanen *et al.*, 2010). Samas ei leitud tugevat seost veetaseme ja emissiooni vahel, kuigi turbakaevandusest mõjutatud aladel oli hüdroloogilise režiimi muutmise tõttu veetase oluliselt madalam ja suurema kõikumisega. Siiski andis statistiline RDA analüüs tulemuse, mille põhjal 67% emissioonist on selgitatav veetaseme ja pinnasetemperatuuriga

10 cm sügavusel. Emissioonid olid sarnased looduslikel ja kuivenduse poolt mõjutatud aladel. Seda eelkõige Soomaal paiknevatel uurimisaladel, kus veetase oli kuivendusaladel sarnane looduslike aladega, kuigi taimestik andis kinnitust kuivenduse mõjudest ja ulatusest. Olulisi erinevust ei leitud ka looduslike ja kuivenduse poolt mõjutatud ning mahajäetud ja aktiivsete turbakaevandusalade vahel (Kruskal-Wallise dispersioonanalüüs), kuigi emissioonid olid kõrgemad kaevandusaladel. Analoogsetes uuringutes on leitud, et võrreldes looduslike aladega, on teatud juhtudel emissioonid turbakaevandusaladel väiksemad, antud asjaolusid on selgitatud värske varise puudumise (Waddington *et al.,* 2001), vähese toitainete sisaldusega ja hästilagunenud turba paljandumisega (Basiliko *et al.,* 2007) ning mikroorganismide vähesusega (Croft *et al.,* 2001). Oluliselt suuremad olid emissioonid suurema taimestiku ja madala veetasemega aladel – Lavassaare turbakaevandusaladel paiknevatel päideroo kasvatusväljakutel, siirdesoomullal paikneval heinamaal ning metsaga kaetud alal Sangla turbakaevandamisalal. Oluliselt väiksem oli emissioon taimestikuta mahajäetud turbakaevandamisalal Lavassaares, kuid seda ka teistel sarnase maakasutusega aladel, kus oli hõre taimestik. Mõõtmistulemuste andmed kaevandusaladelt langevad kokku Soomes ja Rootsis saadud tulemustega – Sundh *et al.* (2000) hindas vegetatsiooniperioodil saadud mõõtmistulemuste põhjal emissiooniks 628 kuni 2787 kg CO_2-C kg ha^{-1} a^{-1}; Shurpali *et al.* (2008) Soomes kahel järjestikusel aastal 3996 ja 5368 kg CO_2-C kg ha^{-1} a^{-1}. Alm *et al.* (2007) hindas olemasolevate emissioonide mõõtmiste ja pikemaajalise õhu- ning mullatemperatuuri (5 cm sügavuselt) simulatsioonide põhjal aastaseks emissiooniks 2672 kg CO_2-C kg ha^{-1} a^{-1} – antud hinnangut kasutatakse ka Soome kasvuhoonegaaside aruande koostamisel (*Greenhouse Gas Emissions in Finland* 2011).

Kuna turbakaevandusaladel puudub taimestik, samuti on vähese või puuduva taimestikuga ka mahajäetud turbakaevandamisalad, andis see võimaluse hinnata saadud mõõtmistulemuste andmete põhjal ka nende alade kasvuhooneefekti tekitava mõju ulatuse. Kasvuhoonegaaside CO_2, CH_4 ja N_2O koguheide CO_2 ekvivalentidesse ümberarvutatuna annab mahajäetud ja aktiivsetelt turbakaevandamisaladelt vastavalt CO_2 osas 6830 ja 6383, CH_4 osas 2 ja 4 ning N_2O puhul 79 ja 88 kg CO_2 ekv ha^{-1} a^{-1}. Siinjuures on CO_2 osakaal ümberarvestatult CO_2 ekvivalentidesse vastavalt 99%. Hinnanguliselt võivad ligikaudu 9371 ja 19,574 ha mahajäetud ja aktiivseid turbakaevandamisalasid emiteerida 191,499 t CO_2 ekv. a^{-1}. Juhul, kui need alad oleksid looduslikus olekus, siis vastavalt Gorhami (1995) hinnangule, mille alusel sood talletavad 23 g C m^{-2} a^{-1}, on nendel aladel lõppenud süsiniku akumuleerumine ulatuses 6657 t C a^{-1} ehk 24,405 t CO_2 a^{-1}. Seeläbi on Eestis kaevandamise poolt rikutud rabade ja siirdesoode kasvuhooneefekt ligikaudu 10 korda suurem kui juhul, mil need alad oleksid endiselt looduslikus olekus.

Süsinikubilanss arvutati ka päideroo istanduse kohta, vajalike andmete saamiseks võeti aladelt biomassi proovid (varise, maa-aluse ja maapealse biomassi analüüsid, sh C, N ja P sisaldus; juurdekasvu hindamiseks võeti proovid sügisel ja kevadel). Kogutud andmete alusel saab väita, et võrreldes turbakaevandusaladega muudab päideroo kasvatamine jääksoodes need alad süsiniku emiteerijast süsiniku akumuleerijaks. Võrreldes teiste uurimisaladega kaasnesid päideroo kasvatamisega oluliselt suuremad CO_2 emissioonid, mis on põhjustatud värske varise olemasolust ja taimede kasvuga kaasneva turba mineraliseerumise kiirenemisest. Uurimistöö käigus kogutud andmete alusel on läbi viidud elutsükli analüüs päideroo kasutamise kohta jääksoodes (Järveoja *et al.,* 2012).

Senised ökosüsteemi ülesed kasvuhoonegaaside mõõtmised turvasmuldadel kasvavates metsades on andnud tulemuseks –890 kuni –900 g CO_2 g m^{-2} a^{-1} (Laurila *et al.,* 2007; Lohila *et al.,* 2011). Siinjuures puude juurdekasv kätkes endas 70% C sidumisest ja ülejäänu osas oletati selle akumuleerumist pinnasesse (Lohila *et al.,* 2011). Antud uuringud annavad taas teavet suhteliselt lühikese perioodi kohta, terviklikuma hinnangu saamiseks turvasmuldadel paiknevate metsade kasvuhoonegaaside bilansi arvutamisel on oluline kogu raieringi käsitlevate uurimiste läbiviimine (Minkkinen *et al.*, 2001).

CH_4-C emissioonid looduslikelt, kuivendatud, mahajäetud ja tegutsevatelt turbatootmisaladelt, päideroo kasvatusaladelt ja siirdesoomullal paiknevalt heinamaalt olid vastavalt 71.1 (23.9–120.8), 23.7 (8.1–137.1), 0.06 (–4.8–20.4), 0.12 (–0.1–6.1), 0.30 (0.20–0.31) ja –1.23 kg CH_4-C ha^{-1} a^{-1} (esitatud mediaani väärtused ja vastava maakasutustüübi all olevate uurimisalade vastavate väärtuste ulatus).

Mõõtmistulemuste põhjal olid CH_4-C vood suuremad looduslikes tingimustes olevatelt aladelt, mis vastas ka erinevate teaduskirjanduses käsitletud mõõtmiste käigus saadud andmetele. Metaani (CH_4) emissiooni määr sõltub veetasemest selle muutustest kas kuivenduse või kuivemate kliimaolude tõttu. Võrreldes kuivendatud ja looduslikke alasid turbakaevandamise aladega, oli viimaste veetase oluliselt madalam. Samas registreeriti Soomaa uurimisaladel oodatust väikseid erinevusi kuivendatud alade ja looduslike soode vahel. Aastaajaliselt registreeriti väiksemad vood vegetatsiooniperioodi välisel perioodil (18%), sarnastele tulemustele on jõudnud ka 15% Saarnio *et al.* (2007) – 15% ja Nilsson *et al.* (2001) – 22%. Oluline osa metaani emissioonis on taimestikul – soontaimede esinemise suurenemisega kasvab emissiooni koguhulk (Strack *et al.*, 2003) tänu taimede poolt õhkkoe abil pakutavale gaasi transpordile katotelmist akrotelmi (Frenzel & Karofeld, 2000; Nilsson *et al.*, 2001). Ka mõõtmisaladel lähtuti proovide kogumisel soontaimede, eelkõige villpea (*Eriophorum*) esinemisest või mitteesinemisest ning mõõtmisandmed kinnitasid suuremaid voogusid villpeaga aladelt.

N_2O-N emissioonid looduslikelt, kuivendatud, mahajäetud ja tegutsevatelt turbatootmisaladelt, päideroo kasvatusaladelt ja siirdesoomullal paiknevalt heinamaalt olid vastavalt –0.05 (–0.06–0), –0.01 (–0.06–0.06), 0.17 (0.02–1.06), 0.19 (0.06–3.97), –0.05 (–0.09–0.02) ja 2.64 kg N_2O-N ha^{-1} a^{-1} (esitatud mediaani väärtused ja vastava maakasutustüübi all olevate uurimisalade vastavate väärtuste ulatus).

N_2O-N emissioonid olid mõõtmisaladelt väikesed, kuid looduslikest ja kuivendatud aladest erinesid oluliselt turbakaevandusalad. Looduslikel ja teistel kuivendatud aladel registreeriti ka N_2O-N sidumist mõõtmisaladel, mida on täheldatud ka teistes uurimustes (Alm *et al.*, 2007; Hayden & Ross, 2005; Martikainen *et al.*, 1993). Väikeste emissioonide kohta looduslikelt aladelt annab kinnitust ka kirjanduse ülevaade. N_2O emissiooni sõltub eelkõige vajalike toitainete – nitraadi kättesaadavusest, seeläbi on emissioon väike toitainevaestes rabades ja toimub suuremal määral toitainerikkamatelt või kuivendatud aladelt. Oluline seos leiti suuremate emissiooniga aladel turba C : N suhte kohta, mille väärtustel ulatuses 17–27 registreeriti teistest oluliselt suuremad emissioonid. N_2O-N emissioonid turbakaevandusaladelt olid sarnased uuringutele Soomes – 0.03 kuni 0.12 kg N_2O-N ha^{-1} a^{-1} (Hyvönen *et al.,* 2009).

Mõõtmiste käigus saadud andmed annavad lisateavet rikutud soode, eelkõige turbakaevanduste osast kasvuhoonegaaside emiteerija või sidujana ja seeläbi ka kliima kujundajana. Saadud andmete põhjal saab väita, et Eesti siirdesoode ja rabade poolt osutatav ökosüsteemi teenuse – CO_2 sidumine atmosfäärist fotosünteesi abil ja süsiniku akumuleerumine – koguhulk on oluliselt vähenenud, seda eelkõige turbakaevandamise läbi ja sellel on kasvuhooneefekti tekitav mõju. Järeldusena tuleb rõhutada, et jääksoode kasutamata jätmine on oluliseks kasvuhoonegaaside lendumise põhjustajaks. Seetõttu on vajalik mahajäetud kaevandamisaladel kas turvas lõpuni kaevandada või siis taastada neid viisil, mis gaaside emissiooni vähendaks. Kuigi Eesti looduslikuna säilinud sood on suhteliselt hästi kaitstud, on siiski oluliseks väljakutseks edasiste tegevuste kavandamine, mille abil vähendada kuivenduse tõttu muudetud aladel kasvuhoonegaasi emissioone. Nende hulka kuulub ka kuivenduse tõttu rikutud alade taastamine, kus kaevandamist pole toimunud. Kogutud andmed võimaldavad hinnata kasvuhoonegaaside voogude muutusi soode taastamisel – Kuresoo uurimisalal Soomaa Rahvuspargis on alanud 70 ha suurusel kuivendusobjektil tööd raba taastamiseks.

Eesti soodest lähtuvate kasvuhoonegaaside voogude hindamiseks on jätkuvalt vajadus viia läbi pikaajalisemaid, aastate vahelist varieeruvust arvestavad mõõdistusi erinevates sootüüpides ja maakasutusviisiga aladel. Oluline on siinkohal ökosüsteemi ülesed mõõtmised, mis aitavad hinnata fotosünteesi käigus taimedesse ja varise kaudu mulda akumuleeruva süsiniku hulka, seda eelkõige metsaga kaetud aladel. Täiendavalt vajavad hindamist kuivendatud soodest saadava turba ja puidu osa nende alade süsinikubilansis, mis peab kätkema endas vastavalt ka elutsükli analüüsi. Päideroo kasutusvõimaluste kohta on uurimistöö käigus kogutud mõõtmisandmetele tuginedes nende analüüsidega alustatud (Järveoja *et al.,* 2012).

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PUBLICATIONS

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Publications

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Mander, Ü., Järveoja, J., Maddison, M., Soosaar, K., Aavola, R., Ostonen, I., Salm, J.-O. 2012. Reed canary grass cultivation mitigates greenhouse gas emissions from abandoned peat extraction areas. Glob. Change Biol. Bioenergy. DOI: 10.1111/j.1757-1707.2011.01138.x.

Mander, Ü., Uuemaa, E., Kull, A., Kanal, A., Maddison, M., Soosaar, K., Salm, J.-O., Lesta, M., Hansen, R., Kuller, R., Harding, A., Augustin, J. 2010. Assessment of methane and nitrous oxide fluxes in rural landscapes. Landscape and Urban Planning, 98(3–4): 172 – 181.

Salm, J.-O., Soosaar, K., Maddison, M., Tammik, S., Mander, Ü. 2010. Kasvuhoonegaasid ja süsiniukukaod Eesti soodest. Eesti Loodus 9: 422–427. *In Estonian.*

Salm, J.-O., Kimmel, K., Uri, V., Mander, Ü. 2009. Global warming potential of drained and undrained peatlands in Estonia: a synthesis. Wetlands 29(4):1081–1092.

Kimmel, K., Kull, A., Salm, J.-O., Mander, Ü. 2009. The status, conservation and sustainable use of Estonian wetlands. Wetlands Ecology and Management 18 (4): 375–395.

Salm, J.-O., Soosaar, K., Maddison, M., Mander, Ü. 2009. Kasvuhoonegaaside CO_2, CH_4 ja N_2O emissioon looduslikest ja kuivendatud soodest ning turbatootmisaladelt. In: Mander, Ü.; Uuemaa, E.; Pae, T. (eds.) Uurimusi eestikeelse geograafia 90. aastapäeval. Tartu, 2009. (Publicationes Instituti Geographici Universitatis Tartuensis; 108). Tartu Ülikooli geograafia osakond, Tartu, lk. 360–378. *In Estonian.*

Salm, J.-O., Mander, Ü. 2008. Kasvuhoonegaaside CO_2, CH_4 ja N_2O emissioon siirdesoodest ja rabadest: võimalikud muutused Eesti ökosüsteemide teenustes. In: Pae, T., Mander, Ü. (eds.) Publicationes instituti Geographici Universitatis Tartuensis 105. Tartu Ülikooli geograafia osakond, Tartu, lk. 20–66. *In Estonian.*

Societal activities

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1. Peamised uurimisvaldkonnad:
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2. Publikatsioonide loetelu:

Salm, J.-O., Maddison, M., Tammik, S., Soosaar, K., Truu, J., Mander, Ü. 2012. Emissions of CO_2, CH_4 and N_2O from undisturbed, drained and mined peatlands in Estonia. Hydrobiologia. DOI: 10.1007/s10750-011-0934-7.

Mander, Ü., Järveoja, J., Maddison, M., Soosaar, K., Aavola, R., Ostonen, I., Salm, J.-O. 2012. Reed canary grass cultivation mitigates greenhouse gas emissions from abandoned peat extraction areas. Glob. Change Biol. Bioenergy. DOI: 10.1111/j.1757-1707.2011.01138.x.

Mander, Ü., Uuemaa, E., Kull, A., Kanal, A., Maddison, M., Soosaar, K., Salm, J.-O., Lesta, M., Hansen, R., Kuller, R., Harding, A., Augustin, J. 2010. Assessment of methane and nitrous oxide fluxes in rural landscapes. Landscape and Urban Planning, 98(3–4): 172 – 181.

Salm, J.-O., Soosaar, K., Maddison, M., Tammik, S., Mander, Ü. 2010. Kasvuhoonegaasid ja süsiniukukaod Eesti soodest. Eesti Loodus 9: 422–427.

Salm, J.-O., Kimmel, K., Uri, V., Mander, Ü. 2009. Global warming potential of drained and undrained peatlands in Estonia: a synthesis. Wetlands 29(4):1081–1092.

Kimmel, K., Kull, A., Salm, J.-O., Mander, Ü. 2009. The status, conservation and sustainable use of Estonian wetlands. Wetlands Ecology and Management 18 (4): 375–395.

Salm, J.-O., Soosaar, K., Maddison, M., Mander, Ü. 2009. Kasvuhoonegaaside CO_2, CH_4 ja N_2O emissioon looduslikest ja kuivendatud soodest ning turbatootmisaladelt. In: Mander, Ü.; Uuemaa, E.; Pae, T. (toim.). Uurimusi eestikeelse geograafia 90. aastapäeval. Tartu, (Publicationes Instituti Geographici Universitatis Tartuensis; 108). Tartu Ülikooli geograafia osakond, Tartu, lk. 360–378.

Salm, J.-O., Mander, Ü. 2008. Kasvuhoonegaaside CO_2, CH_4 ja N_2O emissioon siirdesoodest ja rabadest: võimalikud muutused Eesti ökosüsteemide teenustes. In: Pae, T., Mander, Ü. (toim.) Publicationes instituti Geographici Universitatis Tartuensis 105. Tartu Ülikooli geograafia osakond, Tartu, lk. 20–66.

Ühiskondlik tegevus

11/2007 – …	SA Keskkonnaõiguse Keskuse nõukogu liige
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