DISSERTATIONES GEOGRAPHICAE UNIVERSITATIS TARTUENSIS
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Greenhouse gas fluxes in rural landscapes of Estonia

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ABSTRACT

The topic of planetary shifts in climate resulting from anthropogenic sources has received increasing attention in recent times because elevated levels of greenhouse gases in the stratosphere may be affecting the Earth's climate. The discharge of the greenhouse gases (GHG) carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) is a thoroughly studied environmental phenomenon. Globally, there are a multitude of studies that have concentrated on different aspects of this topic. In this PhD dissertation, a literature review and synthesis of findings was completed based on 950 study sites/experiments from the temperate and boreal zone published between 1980 and 2009 in 165 scientific papers indexed by the ISI Web of Science. This database made it possible to distinguish and analyse the sites according to their land use.

According to the literature analysis, the most intensive methane emitters were natural peatlands and marshes (106 kg CH_4-C ha^{-1} yr^{-1}), whereas nitrous oxide was mainly emitted from drained (partly restored) peatlands and marshes (7.2 and 6.5 kg N_2O-N ha^{-1} yr^{-1} respectively), followed by conventional arable lands on hydromorphic soils (4.5 kg N_2O-N ha^{-1} yr^{-1}), fertilized grasslands (4.2–4.7 kg N_2O-N ha^{-1} yr^{-1}) and coniferous forests on hydromorphic soils (3.8 kg N_2O-N ha^{-1} yr^{-1}).

Further research for this thesis was focused on examining hot spots of GHG emissions in Estonian agricultural landscapes. The direct measurement of GHG fluxes in Estonia have thus far been performed on nutrient-rich systems such as riparian buffer zones and constructed wetlands designed for the treatment of wastewater (Mander et al., 2003, 2005a and b; Teiter and Mander, 2005). In this dissertation 14 different study sites were selected according to different land-use types in Estonia, and their CO_2, CH_4 and N_2O emission rates were measured. In addition, soils were classified as either automorphic or hydromorphic based on their structure. All of the study sites were grouped as follows: of automorphic soils: intensively fertilized arable, abandoned arable land, grassland, fertilized grassland, riparian forests, and of hydromorphic soils: grassland, semi-natural grassland, and riparian forests. Furthermore, two areas, transition fen forests and fen grasslands, which are influenced by drainage, were chosen. Carbon dioxide emissions were considered only as a sum of soil and plant respiration. C sequestration by plant photosynthesis was not considered.

The fluxes of all three gases- CO_2, N_2O and CH_4- varied remarkably at both temporal and spatial scales, and were strongly influenced by changes in environmental conditions.

Fluxes of CO_2 and CH_4 showed different seasonal variations throughout all of the studied groups. Emissions of CO_2 were strongly correlated with soil temperature (through all of the study sites; R^2=0.72), and hence the emissions were higher in the summer season. In the case of CH_4, a different pattern was seen for automorphic soils, which frequently acted as a sink for CH_4, whereas hydromorphic soils were shown to behave as emitters of methane.

In the case of N_2O, no clear differences were found between colder and warmer periods; N_2O was emitted throughout the whole year.

The Kruskal-Wallis test, when applied to determine if there was a statistically important difference between the sites, revealed a significant variance in CH_4 and N_2O emissions. The highest CH_4 emissions were detected from deciduous (riparian alder) forests on hydromorphic soil and drained fen grassland, especially before drainage. The hot spots of N_2O were drained fen forests, fertilized arable land and riparian forests on automorphic soils, which emit significantly more N_2O than other studied groups.

In the case of CO_2 emissions, there was no significant difference between groups, hence the slightly less conservative Duncan test was used. The results showed that the highest emissions of CO_2 came from grassland on automorphic soil.

A significant Spearman rank correlation was found between mean monthly air temperature (MAT) and CO_2, CH_4 and N_2 fluxes from the riparian grey alder forest in Porijõgi and between the MAT and N_2O flux in a similar riparian ecosystem in Viiratsi, and between the monthly precipitation and CH_4 fluxes at both riparian study sites. Groundwater levels higher than 20 cm from the surface significantly increased CH_4 emissions and decreased CO_2 and N_2O emissions. In Porijõgi, where uphill fields have been abandoned since 1996, GHG emissions did not display any discernable trend, whereas in Viiratsi a significant increase in CO_2 and N_2O emissions were found. This may be the result of the age of the grey alder stands (30–40 years in Porijõgi, 60–70 years in Viiratsi), but may also be caused by the long-term nutrient load in the riparian alder stand in Viiratsi (uphill fields still intensively fertilized), which indicates a need for the management of similar, heavily loaded riparian alder land areas.

The average N_2O fluxes from the (former) wastewater treatment reedbed in Matsalu were relatively low, varying from –5.0 to 3.7 µg N_2O m^{-2} h^{-1}. The spatial-temporal variation of CH_4 emission was great (10.5–16397 µg CH_4 m^{-2} h^{-1}), showing higher values in the inflow. The average CO_2 emission from the reedbed varied from 14.3 to 334 mg CO_2-C m^{-2} h^{-1}. This was somewhat higher in the inflow area.

1. INTRODUCTION

Methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2) are important components of the atmosphere and earth's radiation budget. The recent rapid increases in the atmospheric concentrations of these major greenhouse gases (GHG) are contributing significantly to global warming (IPCC, 2007).

In the terrestrial ecosystem's carbon cycle, atmospheric CO_2 is fixed into sugars by the autotrophic (mainly plant) communities in the presence of sunlight. At the same time, plants release a large portion of fixed carbon to the atmosphere through autotrophic respiration. Along with the release of a substantial portion of newly fixed carbon through their roots, plant litter forms a major source of energy for soil heterotrophs, including microorganisms and animals. This carbon pool is respired back to the atmosphere through heterotrophic respiration. A smaller amount of organic carbon remains unused and is stored in the soil. Some organic carbon is also used by some microorganisms for energy, but at a slower rate (Boone et al., 1998; Lambers et al., 1998; Hanson et al., 2000; Brajesh et al., 2010).

The CH_4 cycle involves the conversion of organic residues (sugars) into CH_4 by methanogenesis, which is mainly carried out by a specialized group of archaea called methanogens under anoxic conditions. Most CH_4 produced in soils is, however, immediately oxidized by methanotrophs (Brajesh et al., 2010). The soil surface CH_4 fluxes depend on the balance between production by methanogenic microbes at anaerobic microsites and consumption by methanotrophic microbes at aerobic microsites (Hanson et al., 1993; Le Mer and Roger, 2001). Closely related to the methanogens are the anaerobic methane oxidizers, which utilize methane as a substrate in conjunction with the reduction of sulfate and nitrate (Thauer and Shima, 2006). Most methanogens are autotrophic producers, but those that oxidize CH_3COO^- are instead classified as chemoheterotrophs.

The greenhouse gas N_2O has a global warming potential 296 times greater than CO_2. Nitrous oxide is increasing in the atmosphere at a rate of 0.3% a year, and the gas is anticipated to be responsible for about 5% of total global warming potential (IPCC, 2007). The substrates for nitrous oxide production, ammonium (NH_4^+) and nitrate (NO_3^-), enter soils in various forms. Atmospheric dinitrogen (N_2) is fixed by soil microorganisms in a process where it is converted to NH_4^+; alternatively, reactive forms (mainly NO_3 and NH_3) can be deposited in precipitation or as dry deposition. Sources of N_2O can also be released from organic residues from plants and animals, animal waste and nitrogen fertilizers (Brajesh et al., 2010).

Nitrous oxide is emitted from soils via microbial processes during nitrification under aerobic conditions and denitrification under anaerobic conditions. Generally, denitrification is considered to be the more significant contributor to N_2O emissions, where it is emitted when the final reduction in the denitrification pathway from N_2O to N_2 is not completed. Interactions between the individual variables controlling these processes will regulate the quantity and rates of N_2O and N_2 end-product formation (Soosaar et al., 20XX, Publication II; Davidson et al., 2000; Firestone and Davidson, 1989).

N_2O, CO_2, and CH_4 fluxes are highly variable and strongly influenced by changes in environmental conditions such as temperature, soil moisture, carbon availability, NO_3^- availability and pH substrate availability (Nommik, 1956; Knowles, 1982; Firestone and Davidson, 1989; Le Mer and Roger, 2001). In addition, these factors are interrelated and may show synergistic relationships (Fleischer and Bouse, 2008).

Understanding and managing regional and global greenhouse gas budgets involves understanding how diverse natural and anthropogenic factors influence the production and consumption of different gases (Groffman and Pouyat, 2009).

1.1. Hot spots of greenhouse gas emissions in rural landscapes

The rural landscape contains both sources and sinks for greenhouse gases. Storage of atmospheric CO_2 in stable organic carbon pools in the soil can sequester CO_2, while commonly-used crop production practices generate CO_2 and N_2O and decrease the soil sink for atmospheric CH_4 (Mosier et al., 2005). In addition, agricultural soils are typically minor emitters of CH_4, and generally small sinks for atmospheric CH_4 (Bronson and Mosier, 1993). Meanwhile, abandoned agricultural lands on peat soils (Ambus and Christensen, 1995) can be large sources of methane. On a 100-year time horizon, CH_4 has a global warming potential of 24.5 relative to CO_2, and is responsible for about 5% of anticipated warming (IPCC, 2007).

Emissions of CH_4 have the widest scale of variation. For example, according to the literature, unfertilized grasslands on automorphic soils have the highest capacity to oxidise methane. The average annual values may vary from –37.23 kg CH_4-C ha^{-1} yr^{-1} in reclaimed meadows (Jacinthe and Lal, 2006) to 1761 kg CH_4-C ha^{-1} yr^{-1} in freshwater marshes (Ding et al., 2004a,b). In addition, natural peatlands, drained peatlands and wetlands may also be seen as hot spots for methane (Mander et al., 2010, Publication I). The highest emissions of N_2O have been described by Flessa et al. (1998). The annual emission of N_2O in a rye field in Germany was 67 kg N_2O-N ha^{-1} yr^{-1}.

1.2. Riparian buffer zones

Riparian buffer zones, which act as the interface between terrestrial and aquatic components of the landscape, are important ecotechnological measures to control water quality in agricultural catchments (Kuusemets and Mander 1999) and provide other landscape ecological functions (Mander et al., 2005a). Although the water purification effect of riparian ecosystems has been thoroughly studied (Lowrance et al., 1983; Peterjohn and Correll 1984; Haycock and Pinay, 1993; Vought et al., 1994; Mander et al., 1995, 1997a), their role as greenhouse gas sources needs to be better understood (Groffman et al., 1991; Teiter and Mander 2005; Mander et al., 2008). According to some studies, water purification efficiency can be less favourable in riparian zones, which function as hot spots of greenhouse gas emissions with high global warming potential (Groffman et al., 2000).

The literature review carried out by Soosaar et al. (2011; Publication III) shows that the emission rate from riparian buffer zones can vary from 20.6 kg CO_2-C ha^{-1} yr^{-1} in semi-arid sub-tropical riparian bush and grassland vegetation (McLain and Martens, 2006) to 11400 kg CO_2-C ha^{-1} yr^{-1} in a temperate riparian poplar plantation (Tufekcioglu et al., 2001).

Methane fluxes vary from –5.3 kg CH_4-C ha^{-1} yr^{-1} in riparian northern hardwood forest (Hopfensperger et al., 2009) to 420 kg CH_4-C ha^{-1} yr^{-1} in the permanently inundated zone of a created riparian marsh (Altor and Mitsch, 2006). However, the pulsing hydrological regime significantly decreases methane emission from riparian wetlands (Altor and Mitsch, 2006).

The nitrous oxide flux appears to be the highest among the studied GHGs: from –1.8 kg N_2O-N ha^{-1} yr^{-1} in riparian mixed forest-grass vegetation (Dhondt et al., 2004) to 6390 kg N_2O-N ha^{-1} yr^{-1} in an intensively managed riparian grassland in New Zealand (Schipper et al., 1993). Riparian created marshes showed significantly less N_2O emission (Hernandez and Mitsch, 2006) than natural fens and grasslands (Blicher-Mathiesen and Hoffmann, 1999; Burt et al., 1999; van Beek et al., 2004; Oehler et al., 2007). Alder stands showed the highest N_2O emission values among riparian forests (Teiter and Mander, 2005; Hefting et al., 2006; Mander et al., 2006). The percentage of N_2O flux of N input to the riparian ecosystem varied from 0.02% in a riparian wetland (Jacinthe et al., 1998) to 5.5% in a riparian forest (Jordan et al., 1995).

Several studies take into consideration CO_2 emissions and sequestration in riparian wetlands (Mitsch and Gosselink, 1993) and buffer zones (Brumme et al., 1999; Gulledge and Schimel, 2000; Tufekcioglu et al., 2001; Larmola et al., 2003; Scott et al., 2004; Teiter and Mander, 2005; von Arnold et al., 2005). Depending on meteorological and hydrological conditions, riparian ecosystems, especially wetlands, can be either sources or sinks of carbon (C) (Gulledge and Schimel, 2000).

1.3. Constructed wetlands for wastewater treatment

Wetlands have become increasingly frequently used throughout the world for primary, secondary or tertiary treatment of municipal, domestic, industrial or agricultural wastewaters (Jenssen et al., 1993; Kadlec and Knight, 1996; Vymazal et al., 1998; Soosaar et al., 2009, Publication IV)

Reedbeds as common treatment wetlands offer several important ecological services (Kadlec and Wallace, 2008). They can be used to filter pollution and sewage from water, or also absorb toxic or agricultural run-off (Vymazal et al., 1998). Reedbeds used as wastewater treatment wetland systems are able to improve the quality of wastewater through various processes. In such processes, organic materials and nitrogen are largely removed through volatilization to various gaseous substances, such as CO_2, CH_4, N_2, N_2O, NO and NH_3. The gases are emitted from waterlogged soil either by diffusion through the water or by active transport through the culms of wetland plants. Many species of emergent macrophytes such as *Phragmites australis* possess a convective flow mechanism; oxygen is transported to the roots, and gaseous microbial by-products are emitted into the atmosphere from the plant's roots (Brix et al., 2001).

Constructed and (semi-) natural wetlands are claimed to be effective water purifiers that have lower maintenance costs than those of conventional systems (Kadlec and Wallace, 2008), but at the same time, wetlands can contribute to global warming by emitting both CO_2, CH_4 and N_2O (Fey et al., 1999; Johansson et al., 2002; Johansson et al., 2004; Tai et al., 2002; Mander et al., 2003; Mander et al., 2008; Teiter and Mander, 2005; Liikanen et al., 2006; Picek et al., 2007; Søvik et al., 2008; Wang et al., 2008).

1.4. Research objectives

The overall objective is to improve the understanding of the extent to which land use can influence the emission of greenhouse gases from agricultural areas and unstudied natural ecosystems. The direct measurement of the emissions of these gases in Estonia has so far only been performed for nutrient-rich systems such as riparian buffer zones and constructed wetlands designed for the treatment of wastewater (Mander et al., 2003, 2005a and b; Teiter and Mander, 2005).

The main objectives undertaken were:

- to assess and analyse CH_4 and N_2O fluxes from the main land-use types of rural landscapes using data derived from the existing literature;
- to quantify CO_2, CH_4 and N_2O emission rates in different Estonian landscapes;
- to observe and analyse the temporal pattern of each gas;
- to compare CO_2, CH_4 and N_2O trends and determine hot spots for each gas, especially in case of N_2O and CH_4.

2. MATERIALS AND METHODS

The results of a literature review (Publication I) and three field studies (Publication II; Publication III; Publication IV) are presented in this dissertation. In the following sub-sections, the fieldwork methodology, literature analysis and statistical analysis are described.

2.1. Literature analysis

The literature review (Publication I) consists of 165 scientific papers from the early 1980s to 2008 indexed by the ISI Web of Science and covering at least a one-year period. Analyses that permitted the creation of an annual estimate were chosen for analysis.

All papers considering CH_4 and N_2O fluxes from arable land, grasslands, abandoned (set aside) agricultural land, forests, peatlands and freshwater marshes were taken into account.

The whole database made it possible to distinguish between the following land use types: (1) intensively used arable land (conventional farms and areas with high rates of application of mineral fertilizers); (2) less intensively used arable land (organic agriculture and minimally fertilised conventional fields); (3) intensively managed (fertilised) grasslands; (4) less intensively managed (mostly unfertilised) grasslands; (5) abandoned (set-aside) agricultural land; (6) deciduous forests; (7) coniferous forests; (8) mixed deciduous-coniferous forests; (9) fens and transitional fens; (10) raised/oligotrophic bogs and woodland bogs; (11) freshwater marshes; (12) various peatlands (drained and restored peatlands, peat production areas).

Land use types 1–8 were analysed for both automorphic soils (a wide spectrum of Luvisols, Planosols, Leptosols, Cambisols, Podzols) and hydromorphic soils (Gleysols and Histosols). In the area of peatlands and marshes (types 9–11), both undisturbed and drained variants were taken into account.

2.2. Fieldwork methodology

The fieldwork was carried out at 13 different sites, including microsites (Fig. 1).

1. Drained fen grassland on hydromorphic soil (Sapric Histosols (eutric)) in Aardlapalu (Publication II).
2. Riparian grey alder (*Alnus incana*) forest in Porijõgi (Publications II, III):
   - on automorphic soil (Thapto-mollic Endogleyic Umbrisol);
   - on hydromorphic soil (Thapto-mollic Gleysol).
3. Riparian grey alder (*Alnus incana*) forest in Viiratsi (Publications II, III):
   - on automorphic soil (Thapto-mollic Endogleyic Umbrisol);
   - on hydromorphic soil (Mollic Gleysol; pachic, colluvic).

4. Agricultural fields in Pudivere (Publication II):
   - fertilized arable land on automorphic soil (Haplic Cambisol);
   - grassland on automorphic soil (Haplic Luvisol).
5. Wet grassland in Pudivere (Publication II):
   - semi-natural grassland on hydromorphic soil (Umbric Histic Gleysol).
6. Fertilized arable land on automorphic soil (Endogleyic Cambisol) in Rõhu (Publication II).
7. Abandoned arable land on automorphic soil (Endogleyic Planosol) in Rõka (Publication II).
8. Riparian alder forest on hydromorphic soil (Sapric Rheic Histosol) in Rõka (Publication II).
9. Fertilized grassland on automorphic soil (Haplic Cambisol (calcaric, chromic)) in Sangla (Publication II).
10. Drained transition fen forest (Hemic Hisosols (dystric)) in Sangla (Publication IV).

In order to measure the GHG fluxes, the closed chamber method was used, and the depth of the groundwater table and soil temperature were measured in simultaneously with sampling. In September 2009, the soil types were determined, and soil samples were taken to analyze for the content of the main nutrients N_{tot} and C in the uppermost soil layer.

In addition, to understand the fluxes of GHG from wastewater treatment systems, a semi-natural reedbed locating (former municipal wastewater treatment site) on hydromorphic soil (Mollic and Calcaric Gleysols) in Matsalu was studied (Publication IV).

2.2.1. Detailed description of study sites

Throughout the period 2007–2010, sampling was carried out at the following study sites. The locations of the study sites are shown in Figure 1.

The Aardlapalu study site (drained fen grassland in an abandoned polder) is 1018 ha in size and is situated in south-eastern Estonia (Tartu County, Reola; 58°18′N, 26°44′ E). The whole area is covered with a drainage system. In April and May, the site is flooded with water from the winter snow thaw. The water level is approximately 75 centimeters to 1 meter above the ground. In midsummer, usually at the end of July, it is drained and the resulting grassland is used mainly for haying (Publication II).

The Porijõgi study site represents a grey alder stand. It is situated in the moraine plain of south-eastern Estonia (Tartu County, Sirvaku; 58º 13` N, 26° 47` E), in the riparian zone of a small river, the Porijõgi, which flows in a primeval valley where agricultural activities ceased in 1992. The landscape study transect in this valley crosses an area of abandoned arable land and an abandoned cultivated grassland. In the grey alder stand, 3 microsites: wet, dry and edge, were chosen for gas and soil analyses (Publications II, III). In this thesis, however, only the first two will be discussed (edge: riparian forest on automorphic soil, and wet: riparian forest on hydromorphic soil). A more detailed description of the site is given in Publication III.

The Viiratsi study site is situated in the Sakala uplands (Viljandi County, 58º 20` N, 25° 39` 20'' E), consisting of moraine hills and undulated plains with a variety of glacial deposits. The study area is located on the moraine plain in the vicinity of a pig farm (30 000–80 000 pigs at the time of the study). Almost all of the slurry from the pig farm is spread on the neighbouring fields, and the whole area is heavily impacted by the pig slurry. The site includes a land transect located in a cultivated field, where slurry is spread almost every growing season. At this site, three microsites: wet, dry and slope, were chosen for gas and soil analyses (Publication II, III); only the first two of these, however, are included in this thesis (dry: riparian forest on automorphic soil, and wet: riparian forest on hydromorphic soil). A more detailed description of this site is given in Publication III.

Figure 1. Study sites in Estonia. 1 – Aardlapalu drained fen grassland, 2 – Porijõgi riparian forest on automorphic soil, 3- Porijõgi riparian forest on hydromorphic soil, 4 – Viiratsi riparian forest on automorphic soil, 5 – Viiratsi riparian forest on hydromorphic soil, 6 – Pudivere fertilized arable land on automorphic soil, 7 – Pudivere grassland on automorphic soil, 8 – Pudivere semi-natural grassland on hydromorphic soil, 9 – Rõhu fertilized arable land on automorphic soil, 10 – Sangla fertilized grassland on automorphic soil, 11 – Sangla drained transition fen forest, 12 – Rõka abandoned arable land on automorphic soil, 13 – Rõka riparian forest on hydromorphic soil and 14 – Matsalu semi-natural reedbed on hydromorphic soil.

The Pudivere study site is located in northern Estonia (Lääne-Viru County, Liivaaugu, 59°5′N, 26°22′E). The area is mainly used for agricultural purposes, and all microsites are surrounded with arable fields or grasslands. At this site, 3 microsites have been chosen: fertilized arable land and grassland on automorphic soils, and semi-natural grassland on hydromorphic soil (Publication II).

The Rõhu study site (intensively fertilized arable land) is located in south-eastern Estonia (Tartu County, 58°21′N, 26°31′E). This area is very actively used for agricultural purposes. The main cultivated crops are corn (for silage) and oil rape. In the first year of research, there were two study sites in this area: one that had a manipulated, high groundwater level and another with normal drainage. Since 2009, water-level manipulation ended, and these two microsites are considered as one (Publication II).

The Rõka study site is situated in eastern Estonia (Tartu County, Rõka 58°14′N, 27°18′E). At Rõka, two microsites have been chosen: a former arable field on automorphic soil that was abandoned during the last decade, and a riparian black alder (*Alnus glutinosa*) forest on hydromorphic soil (Publication II).

The Sangla study site is situated in south-eastern Estonia (Tartu County, Rannu 58°19′N, 26°13′E), where the whole neighbouring area is a former peat extraction field. At Sangla, two microsites have been chosen: a grassland area on the slope of mineral soil (the downslope of an arable field) that is influenced by a drainage downslope and is used only for haying (no herding), and a drained transition fen forest at the border of the peat extraction area (Publication II).

The Lihula-Matsalu study site (reedbed; 7 ha), is located on the western coast of Estonia, close to the southern border of Matsalu National Park in Läänemaa County (58°41'N; 23°49'E). The area receives water mainly from the Lihula wastewater treatment plant (WTP) and thus is used as a tertiary wastewater treatment system. Common reed (*Phragmites australis*), the dominant macrophyte of the reedbed, forms patch-like stands of different densities. To a lesser extent, other species such as cattails (*Typha latifolia* and *T. angustifolia*), sedges (*Carex spp.*) and other aquatic macrophytes are also present. The area is regularly flooded (for about 4–6 months of the year). Water flows through the reedbed, forming several pathways of various volume and depth (10–30 cm). For a more detailed description of the site, see Publication IV.

Soil types of the microsites and other relevant characteristics are described in Table 1.

Table 1. Soil type and other relevant characteristics of the soil at the study sites.

	Name of study site and microsites	Soil type	Depth of A-horizon, m	Average groundwater table depth, m	pH KCL of topsoil	C in topsoil, %	N_{tot} in topsoil, %	C/N
1	Aardlapalu drained fen grassland	Sapric Histosols (eutric)	0.2	+0.63– ≤1	nd	16.28	1.39	11.71
2	Porijõgi riparian forest on automorphic soil (edge)	Thapto-mollic Endogleyic Umbrisol	0.25	0.2–0.95	6.30	5.30	0.32	16.56
3	Porijõgi riparian forest on hydromorphic soil (wet)	Thapto-mollic Gleysol	0.35	0–0.09	6.50	4.00	0.41	9.76
4	Viiratsi riparian forest on automorphic soil	Thapto-mollic Endogleyic Umbrisol	0.25	0.3–1.0	7.60	9.10	0.76	11.97
5	Viiratsi riparian forest on hydromorphic soil	Mollic Gleysol (pachic, colluvic)	0.45	0–0.18	4.80	1.40	0.13	10.77
6	Pudivere fertilized arable land	Haplic Cambisol	0.25	–	5.60	2.60	0.21	12.17
7	Pudivere grassland	Haplic Luvisol	0.32	–	6.30	2.34	0.19	12.60
8	Pudivere semi-natural grassland on gleysol	Umbric Histic Gleysol	0.42	0–0.95	5.10	6.55	0.52	12.53
9	Rõhu fertilized arable land	Endogleyic Cambisol	0.3	–	7.0	4.35	0.34	12.74
10	Sangla fertilized grassland	Haplic Cambisol (calcaric, chromic)	0.3	–	6.30	2.69	0.24	11.46
11	Sangla drained transition fen forest	Hemic Histosol (dystric)	–	0.3–≤1	3.90	49.05	2.87	17.12
12	Rõka fallow	Endogleyic Planosol	0.27	0.36–≤1	5	2.22	0.16	13.52
13	Rõka riparian forest on hydromorphic soil	Sapric Rheic Histosol	0.45	+0.05–0.04	4.5	9.77	0.69	14.18
14	Matsalu reedbed (a treatment wetland)	Mollic and Calcaric Gleysols	nd	+0.3–0.1	7.8	18.2	1.33	13.71

In order to obtain a better overview, microsites were grouped according to the land use types. This division is shown in Table 2.

Table 2. Division of microsites into groups.

Name of subside	Group
Rõhu fertilized arable land; Pudivere fertilized arable land	Intensively fertilized arable land on automorphic soil
Rõka abandoned arable land	Abandoned arable land on automorphic soil
Pudivere grassland	Grassland on automorphic soil
Sangla fertilized grassland	Fertilized grassland on automorphic soil
Viiratsi grey alder forest on automorphic soil; Porijõgi grey alder forest on automorphic soil	Riparian forests on automorphic soil
Pudivere semi-natural grassland	Semi-natural grassland on hydromorphic soil
Rõka black alder forest on hydromorphic soil; Viiratsi grey alder forest on hydromorphic soil; Porijõgi grey alder forest on hydromorphic soil	Riparian forests on hydromorphic soil
Sangla drained fen forest	Drained transition fen forest
Aardlapalu drained fen grassland	Drained fen grassland
Matsalu reedbed for wastewater treatment	Treatment reedbed

2.2.2. Sampling and field analyses

The closed chamber method (Hutchinson and Livingston, 1993) was used for the measurement of GHG fluxes. Gas samplers (closed chambers with a cover made of PVC, height and Ø 50 cm, volume 65,5 l, sealed with a water-filled ring on the soil surface, painted white to avoid heating during application) were installed in five replicates at every study site. During each gas sampling session at each microsite, the depth of the groundwater table in the observation wells (Ø 50 mm, 1 m deep PVC pipes perforated and sealed in a lower 0.5 m part) and soil temperature at 4 depths (0–10, 10–20, 20–30 and 30–40 cm) were measured.

Gas sampling was carried out once a month from October to November in 2008, from January to December 2009, and from February to October 2010. It was impossible to take samples from the Aardlapalu drained fen grassland in April 2009 because of the high level of the surface water. Similarly, in April 2010 samples were not taken from the Pudivere microsites due to the fact that there was a thick layer of snow on the ground, approximately 75–100 cm.

The gas samples from the reedbed site were taken in 5 replicates from the middle (from both wet and dry sites) and the outflow of the reedbed in April, June and August of 2007, and once in August 2008 (Fig. 1, Publication IV).

Gas samples were collected with previously evacuated 100 ml gas bottles at 30-minute intervals. Each time the chamber was placed on the ring, the first sample, time zero, was taken, and the next two were taken after 30-minute intervals.

2.2.3. Lab analyses

Gas

The gas concentration in the collected air was determined by using gas chromatography (electron capture detector and flame ionization detector; Loftfield et al., 1997) in the laboratory of the Institute of Technology of the University of Tartu (Publications II, III). In the case of Matsalu, samples were analyzed in the laboratory of the Leibniz Center for Agricultural Landscape Research (ZALF) in Müncheberg, Germany (Publication IV). The emission rates of trace gases were calculated as the difference of gas concentrations between the beginning and the end of measurements, corrected for the area and volume of the chamber (Augustin et al., 1998).

Carbon dioxide emissions have been considered here only as a sum of soil and plant respiration. Carbon sequestration by plant photosynthesis has not been considered.

Soil

In September 2009 (in August 2008 from the reedbed site), soil samples were taken from the topsoil (0–10 cm) at the chamber sites as complex samples (20–30 g soil sampled from five microsites) located in a 0.5 m radius circle, mixed, dried at 60 ^{o}C, and considered as one sample. Nitrogen and carbon concentrations were analyzed in free replicates using the elemental analyzer at the Laboratory of Tartu Environmental Research Ltd.

Soil types were determined according to World Reference Base (WRB) classification.

2.3. Statistical analyses

The statistical analysis was carried out using the Statistica 7.1, Microsoft Office Excel 2007 and Canoco 4.52 programmes.

The normality of variable distributions of all variables was checked using the Kolmogorov-Smirnov, Lilliefors, and Shapiro-Wilk's tests. In most cases, the distribution differed from the normal, and hence non-parametric tests were performed. Medians, 25% and 75% percentile values of variables were also presented.

In the literature overview, the Mann-Whitney U-test was used to test significance when comparing CH_4 and N_2O fluxes from different land-use and soil types.

Kruskal-Wallis ANOVA, multiple comparisons of mean ranks and Duncan test were used to check the significance of the differences between the measured gas fluxes at different microsites, and the Spearman Rank Correlation was used to analyse the relationship between measured GHG fluxes and environmental conditions. In addition, the soft modelling approach called redundancy analysis

(RDA) was applied to relate measured gas emission data to environmental parameters (Legendre and Legendre, 1998). The soil temperature and depth of groundwater data were used in the redundancy analysis as explanatory variables, while microsites were considered as categorical variables.

In addition to Kruskal-Wallis ANOVA, Wilcoxon Matched Pairs tests were used to check the significance of differences between the gas fluxes at riparian microsites

In all cases, $p = 0.05$ was the standard by which statistical significance was accepted.

3. RESULTS AND DISCUSSION

3.1. Literature review

In the literature review the data was divided into different groups according to land use. A more specific description of the division of topics is given in the Material and Methods section. The main results of the assessment of gaseous fluxes (CH_4 and $NO_{2)}$ from various land-use types are described in Fig. 1–7 (Publication I).

3.1.1. Methane

Median values of methane fluxes from arable lands ranged from –0.4 to –0.3 kg CH_4-C ha^{-1} yr^{-1}, showing no significant differences between different management (conventional versus organic) or soil types (automorphic versus hydromorphic soils) (Publication I *Fig. 1*).

In contrast to unfertilized grasslands on automorphic soils, which act as a sink of CH_4 (–1.4 kg CH_4-C ha^{-1} yr^{-1}; Fig. 2), the fertilized grasslands on automorphic soils can be a large source of methane (the median value: 24.3 kg CH_4-C ha^{-1} yr^{-1}) (Publication I *Fig. 2*).

The methane fluxes from set aside and successional areas showed significant differences between automorphic and hydromorphic soils (–1.0 and 0.2 kg CH_4-C ha^{-1} yr^{-1} respectively; Publication I Fig. 3.). In most cases, however, such differences can diminish due to the decreasing efficiency of drainage systems of set aside hydromorphic soils (Dobbie and Smith, 1996; Maljanen et al., 2002, Maljanen et al., 2003; Suwanwaree and Robertson, 2005; Hendriks et al., 2007).

Similarly to grasslands on automorphic soils, different types of forests on automorphic soils reduce atmospheric methane concentrations; the median values of methane varied from –3.5 to –1.5 kg CH_4-C ha^{-1} yr^{-1}, whereas forests on hydromorphic soil emit methane from 1.0 kg CH_4-C ha^{-1} yr^{-1} in coniferous forests to 27.9 kg CH_4-C ha^{-1} yr^{-1} in deciduous forest (Publication I *Fig. 4*)

In comparing methane emissions from automorphic and hydromorphic soils, it is evident that automorphic soils generally act as a sink, except in the case of fertilized grasslands, while hydromorphic soils emit CH_4 to a greater or lesser degree (Publication I *Fig. 1–4*).

The most intensive methane emitters were drained and restored peatlands (262.8 kg CH_4-C ha^{-1} yr^{-1}), followed by natural wetlands (51.7 to 200 kg CH_4-C ha^{-1} yr^{-1}) (Publication I *Fig. 5–6*). Likewise, summer season peaks from bog pools via methane ebullition can on occasion be orders of magnitude higher than the average annual values (Pelletier et al., 2007).

Methane fluxes varied greatly between the different land use types. In comparing all studied land use types, natural peatlands and marshes show significantly higher CH_4 emission values (106 kg ha^{-1} yr^{-1}) than all other types (from -1.7 to 3.7 kg CH_4-C ha^{-1} yr^{-1}) (Publication I *Fig. 4*).

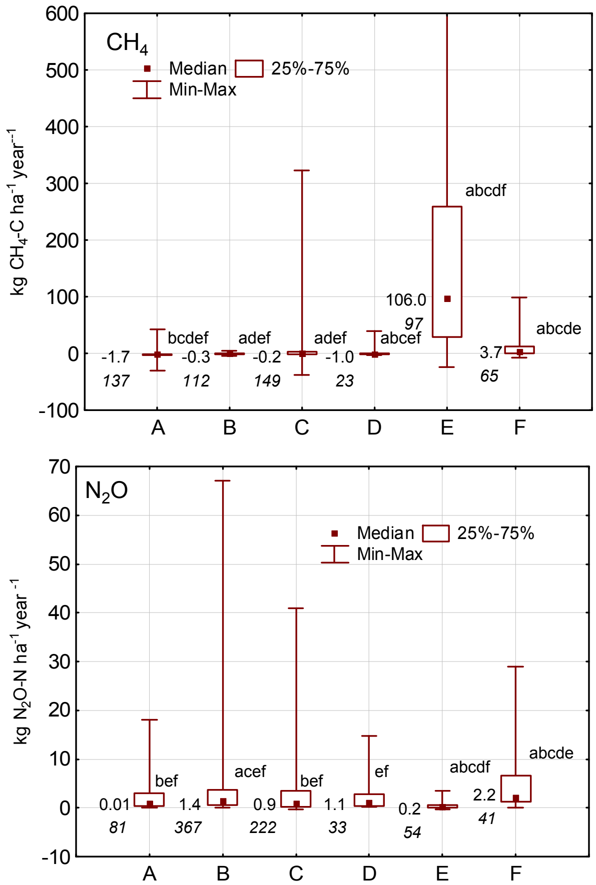


Figure 2. Methane (left) and nitrous oxide (right) emission from different land use types according to the literature analysis (Publication I). A – forest, B – arable land, C – grasslands, D – set aside and successional former agricultural land, E – natural peatlands and marshes, F – drained peatlands and marshes. Letters indicate significantly ($p<0.05$) differing median values (key: a value with 'bcdef' sign differs significantly from B, C, D, E and F values). Regular numbers indicate median values, and italic numbers denote the number of sites/experiments in the analysis.

3.1.2. Nitrous oxide

The highest emissions of nitrous oxide were measured from drained peatlands and marshes (7.2 and 6.5 kg N_2O-N ha^{-1} yr^{-1} respectively; Publication I *Fig. 6*), followed by conventional arable lands on hydromorphic soils (4.5 kg N_2O-N ha^{-1} yr^{-1}; Fig. 1), fertilized grasslands (4.2–4.7 kg N_2O-N ha^{-1} yr^{-1}; Publication I *Fig. 2*) and coniferous forests on hydromorphic soils (3.8 kg N_2O-N ha^{-1} yr^{-1}; Publication I *Fig. 4*). Drained fens/transitional fens (bogs) are also notable sources of N_2O – 2.1 kg N_2O-N ha^{-1} yr^{-1} (Publication I *Fig. 6*).

According to the literature sources, the lowest median values of N_2O were found in natural wetlands: raised/oligotrophic bogs and fens/transitional fens (2.1 and 0.0 kg N_2O-N ha^{-1} yr^{-1} respectively). In most cases, the emissions from autotrophic soils were relatively low: conventional and arable lands (1.1 and 1.4 kg N_2O-N ha^{-1} yr^{-1} respectively), unfertilized grassland (0.3 kg N_2O-N ha^{-1} yr^{-1}) and different forests: deciduous, coniferous and mixed forests (0.5, 0.8 and 1.2 kg N_2O-N ha^{-1} yr^{-1} respectively (Publication I *Fig. 4*).

In general, our study shows that N_2O is predominantly produced in hydromorphic soils. In addition, drained peatlands are a significantly more intensive source than the other land use types (Fig. 2). For more detailed information, see Publication I.

3.2. Hot spots from agricultural landscapes in Estonia

Fieldwork at all sites lasted approximately two years, from November 2008 to October 2010, except at the Viiratsi and Porijõgi alder forest microsites, where samples have been collected since 2001. This dissertation, however, focuses mainly on data collected from the latest period (2008–2010).

The fluxes of all three gases – CO_2, N_2O and CH_4 – varied remarkably at both temporal and spatial scales.

3.2.1. Seasonal differences in CO_2, N_2O and CH_4 fluxes

CO_2

Fluxes of CO_2 show different seasonal variations throughout all studied groups, varying from 0 to 530 mg CO_2-C m^{-2} h^{-1} (Fig. 3). Observed CO_2 fluxes were very low during the winter period, when the soil was frozen and covered with snow, and higher in the vegetative period, between April and October, when soil temperature was higher. This provided more suitable conditions for microbial and fungal communities.

CH_4

The CH_4 fluxes demonstrated higher temporal variability than the simultaneously measured CO_2 or N_2O emission rates. The studied groups showed both high CH_4 uptake rates and emission values that varied from –166 to 55745 µg CH_4-C m^{-2} h^{-1} (Fig. 4–6).

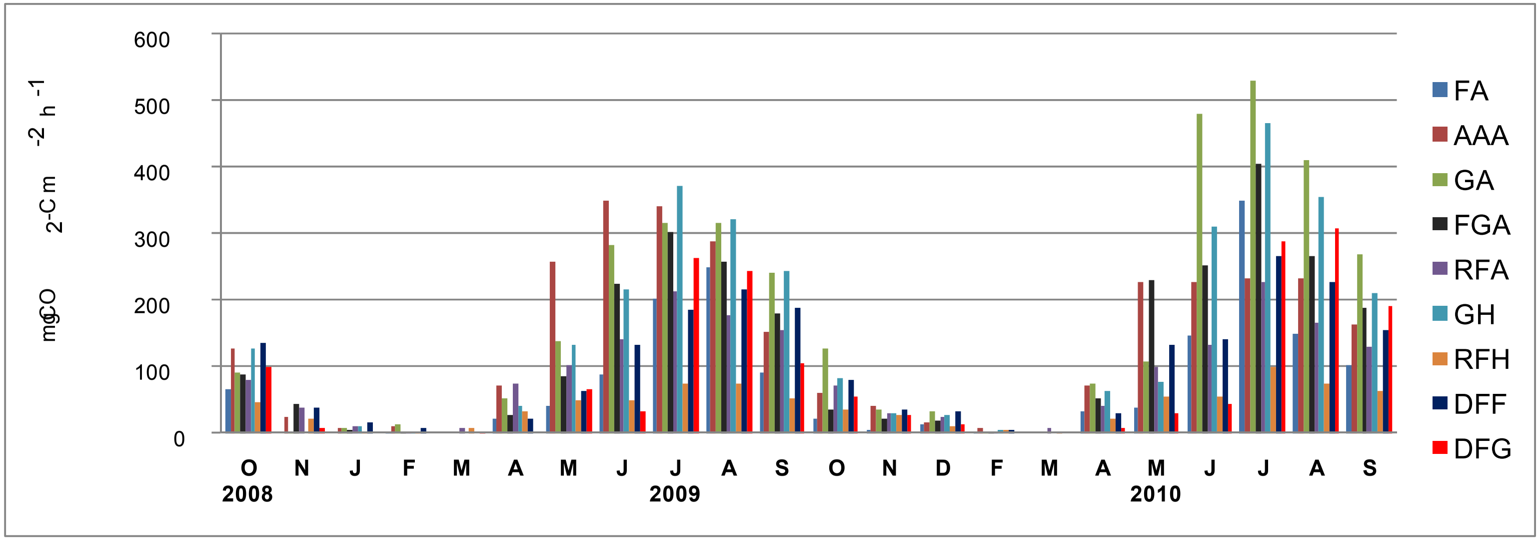


Figure 3. Temporal variations of CO_2 from 2008–2010. FA- fertilized arable land on automorphic soil, AAA- abandoned arable land on automorphic soil, GA – grassland on automorphic soil, FGA – fertilized grassland on automorphic soil, RFA – riparian forest on automorphic soil, GH – grassland on hydromorphic soil, RFH – riparian forest on hydromorphic soil, DFF – drained fen forest, DFG – drained fen grassland.

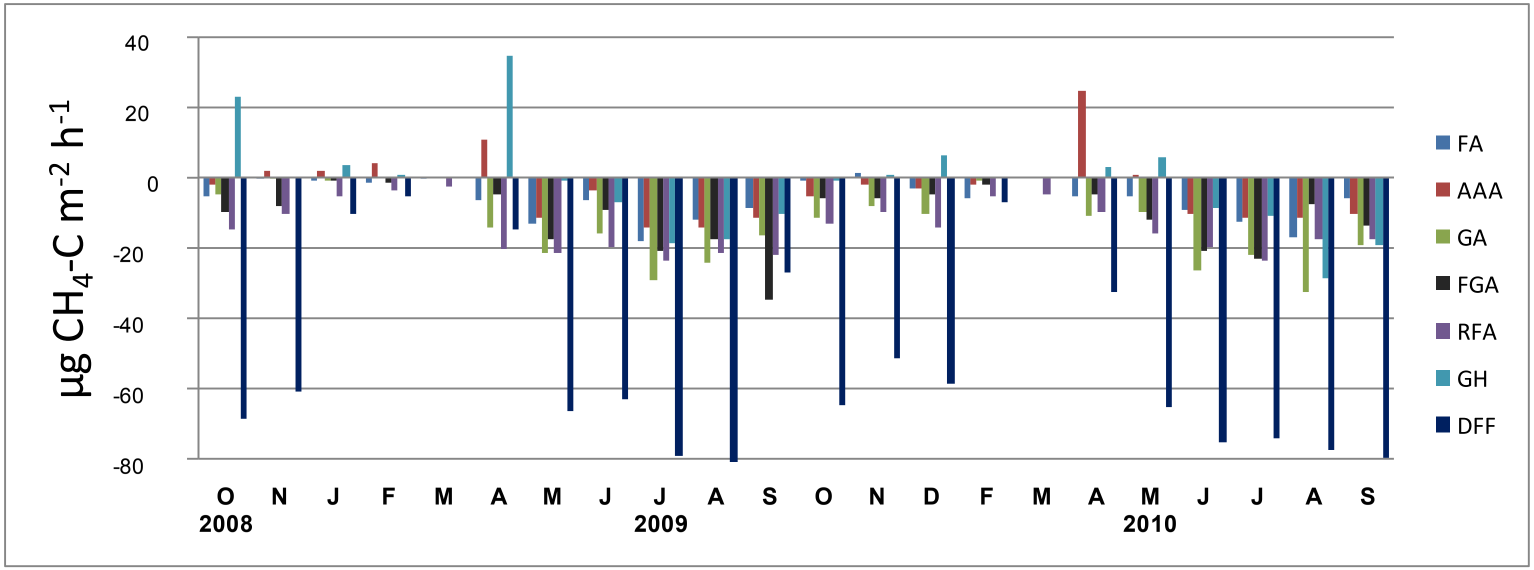


Figure 4. Temporal variation of CH_4 from study sites on automorphic soils and drained fen forest (Sangla) and grassland on hydromorphic soil (Pudivere) in 2008–2010. For abbreviations, see Fig. 3.

Among all of the studied groups, riparian forests on hydromorphic soils (Fig. 5) and drained fen grasslands showed the highest CH_4 emissions and temporal variation. On drained fen grasslands, the emission rates were positive until July, but directly after drainage at the end of July they dropped to negative values (Fig. 6).

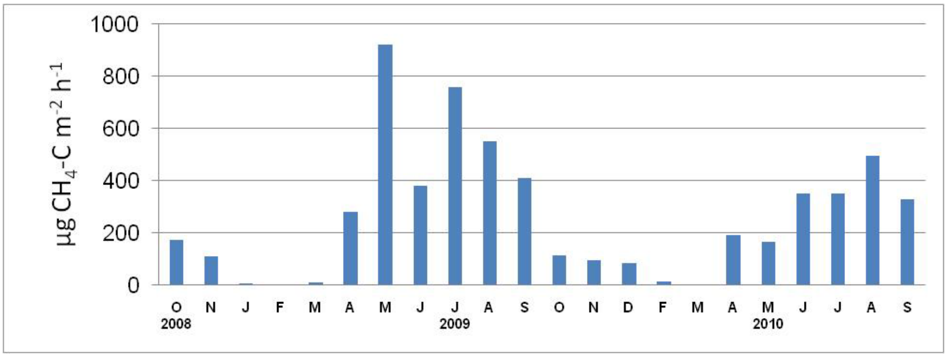


Figure 5. Temporal variation of CH_4 from riparian forests on hydromorphic soil in Porijõgi, Viiratsi and Rõka in 2008–2010.

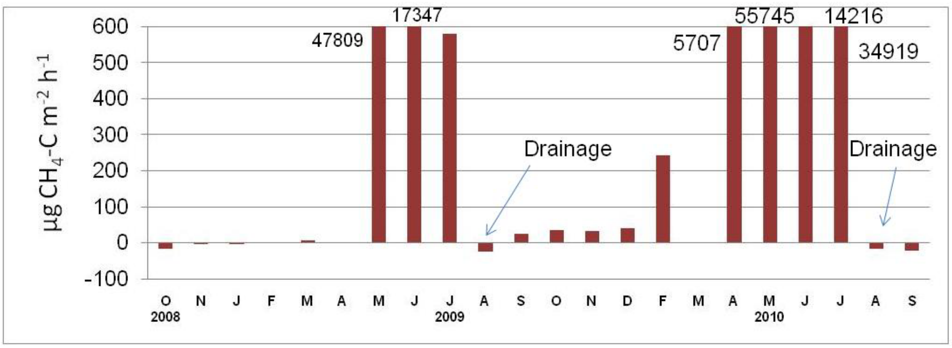


Figure 6. Temporal variation of CH_4 from drained fen grassland in Aardlapalu in 2008–2010.

N_2O

The variation of N_2O indicates that no such clear temporal pattern was found when analysing monthly emissions, which varied from –4.1 to 608 µg N_2O-N m^{-2} h^{-1} (Fig. 7). The highest monthly value was detected in the drained fen grassland in July, just after lowering of the water table. This may have occurred due to the changing of soil conditions from anaerobic to aerobic, where nitrifying bacteria oxidized the available ammonium to N_2O. The lowering of the water table in wetlands is a well-known reason for increased N_2O emissions

(Martikainen et al., 1993). There was also a higher emission of N_2O from fertilized arable land and grasslands just after fertilization.

There was no clear difference between colder and warmer periods. Several studies suggest that a large amount of N_2O can be emitted from various soils, even at temperatures below 0°C (Holtan-Hartwig et al., 2002; Groffman et al., 2006). The main mechanism for N_2O emission in frozen soil is denitrification (Mørkved et al., 2006), whereas N_2O can be produced in unfrozen water films in an anaerobic soil matrix in frozen soil (Teepe et al., 2001). Emission of N_2O in winter may account for more than half of the annual emission in boreal and temperate areas (Röver et al., 1998; Regina et al., 2004). Freezing and thawing cycles significantly increase N_2O emissions (Teepe et al., 2004; Song et al., 2006).

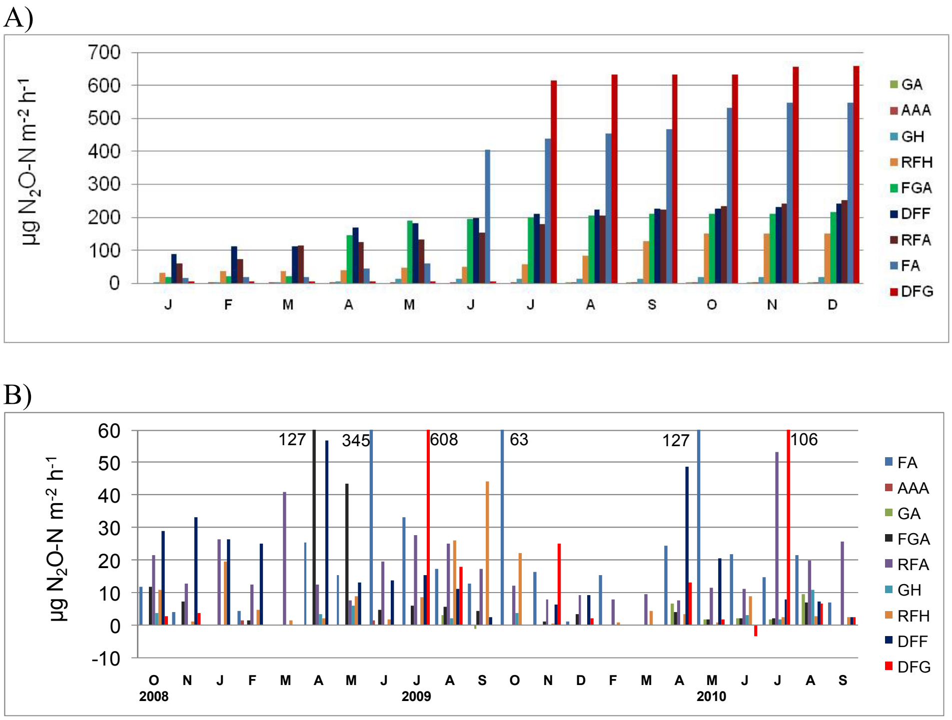


Figure 7. Cumulative N_2O fluxes from study site groups in 2009 (A) and temporal variation of N_2O from 2008–2010. For abbreviations, see Fig. 3.

3.2.2. Spatial differences in CO_2, N_2O and CH_4 fluxes

CO_2

The highest median values of CO_2 were found in abandoned arable land on automorphic soil (median value 8789 kg CO_2-C ha^{-2} yr^{-1}), followed by grasslands on automorphic soils and grasslands on hydromorphic soils (8582 and

6890,9 kg CO_2-C ha^{-2} yr^{-1} respectively). This may best be explained by the amount of plant litter found on these land types. On grasslands and abandoned arable land, greater amounts of litter were present; thus there was more available material for microbes and fungi to decompose (Prevost-Boure et al., 2010).

The lowest median values were found on drained fen grasslands and fertilized arable land on automorphic soils (2811 and 3054 kg CO_2-C ha^{-2} yr^{-1} respectively).

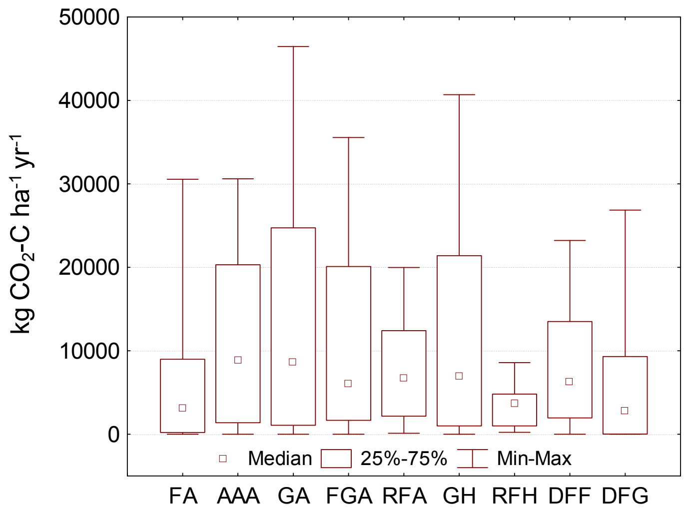


Figure 8. Comparison of cumulative soil and plant respiration CO_2 fluxes between different site groups. The data represents fluxes from all groups. For abbreviations, see Fig. 3.

The Kruskal-Wallis test was applied to determine if there was a statistically significant difference between respiration rates ($P<0.05$). The results showed that in the case of CO_2 emissions there was no significant difference among groups.

The Duncan test, which is slightly less conservative than the Kruskal-Wallis test, showed that grasslands on automorphic soils had significantly higher emissions than fertilized arable land on automorphic soils, riparian forests on automorphic and hydromorphic soils, drained fen forests and grasslands. In addition to grasslands on automorphic and hydromorphic soils, abandoned arable land, fertilized grasslands on automorphic soils and drained fen forests had significantly higher emissions than riparian forest on hydromorphic soil. Likewise, fertilized arable land on automorphic soil differed significantly and had higher emissions of CO_2 than grasslands on hydromorphic soils (Table 3).

Table 3. The results of the Duncan test in comparing CO_2-C emissions. For abbreviations, see Fig. 3.

Duncan test CO_2-C									
Land-use type	FA	AAA	GA	FGA	RFA	GH	RFH	DFF	DFG
FA		0.055	0.003**	0.099	0.668	0.026*	0.181	0.441	0.749
AAA			0.306	0.746	0.118	0.720	0.001**	0.215	0.098
GA				0.200	0.011*	0.463	0.000**	0.029*	0.008**
FGA					0.189	0.524	0.004**	0.319	0.164
RFA						0.063	0.101	0.689	0.888
GH							0.000**	0.127	0.051
RFH								0.048*	0.118
DFF									0.614

CH_4

Riparian forests on hydromorphic soils and drained fen grasslands showed both the highest CH_4 emissions and the greatest temporal variation (Fig. 5). On drained fen grasslands, the emissions were elevated from the spring thaw until July, which was considerably higher than in the other groups (the maximum emissions were in May 2008 and 2009, or 47810 and 55745 µg CH_4-C m^{-2} h^{-1} respectively). After drainage created aerobic conditions, however, the emissions dropped to negative (Fig. 6). This is predictable, as production of methane can only take place in anoxic conditions (Le Mer and Roger, 2001; Brajesh et al., 2010).

The drained fen forest acted as the greatest sink of CH_4 (median value –5.4 kg CH_4-C ha^{-2} yr^{-1}), followed by riparian forests and grasslands on automorphic soils (the median value –1.4 and –1 kg CH_4-C ha^{-2} yr^{-1} respectively).

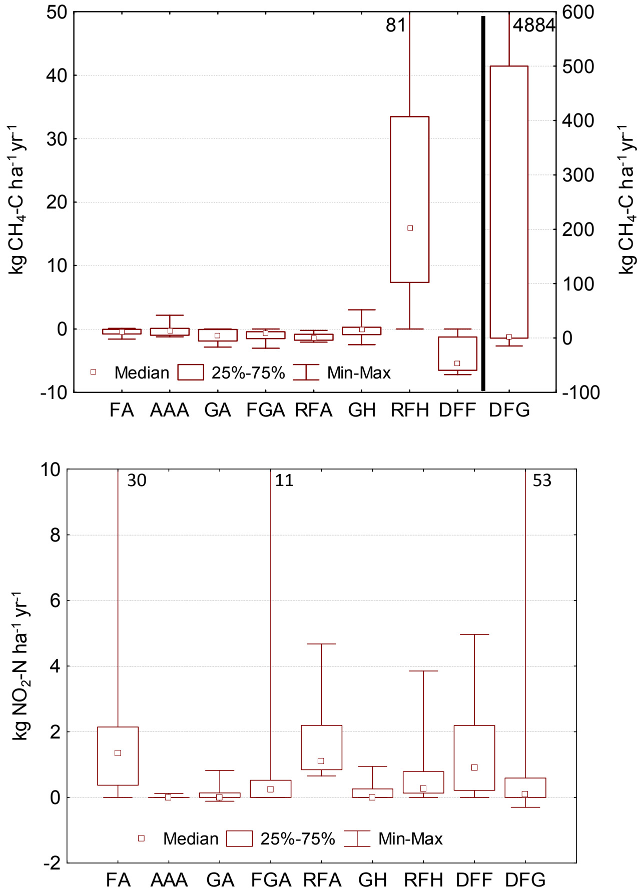


Figure 9. Methane (left) and nitrous oxide (right) emission from all of the study site groups. For abbreviations, see Fig. 3.

CH_4 fluxes, when compared using the Kruskal Wallis test, showed a significant difference between groups. As a follow-up to the Kruskal-Wallis test, multiple comparisons were performed. The results showed that riparian forests on hydromorphic soils had statistically higher emissions than all other groups, except for drained fen grasslands, which emitted statistically more CH_4 than grasslands on automorphic soils, riparian forests on automorphic soils or drained fen forests. In addition, the test results showed that drained fen forests oxidized statistically more CH_4 than fertilized and abandoned arable land or grasslands on hydromorphic soils (Table 3). These results confirm the literature overview, which demonstrated that emissions from deciduous forests, in this case riparian alder forest, on hydromorphic soils have higher emissions of CH_4 than all other land use types, except peatlands and wetlands, which are not included in this part of the dissertation (Publication I).

N_2O

The highest N_2O emissions were found on fertilized arable land (1.4 kg N_2O-N ha^{-2} yr^{-1}), followed by riparian forests on automorphic soils and drained fen forests (1.1 and 0.9 kg N_2O-N ha^{-2} yr^{-1}. There were also high emissions from drained fen grasslands just after drainage and from fertilized grasslands on automorphic soils directly after fertilization, but the annual median values were relatively low (0.24 and 0.08 kg N_2O-N ha^{-2} yr^{-1}) (Fig. 9).

The lowest emissions were from abandoned arable land and grasslands on auto- and hydromorphic soils, where the annual median values were in all cases 0 kg N_2O-N ha^{-2} yr^{-1}.

The comparison of N_2O emissions with Kruskal-Wallis test showed that drained fen forests, fertilized arable land and riparian forests on automorphic soils emit significantly more N_2O than abandoned arable land on automorphic soils or grasslands on automorphic or hydromorphic soils. Likewise, riparian forests on automorphic soils emitted significantly more N_2O than drained fen grasslands or fertilized grasslands on automorphic soils (Table 3).

Table 4. The results of multiple comparisons of mean ranks for all groups of CH_4-C and N_2O-N fluxes. For abbreviations, see Fig. 3.

									CH_4-C
Land type	FA	AAA	GA	FGA	RFA	GH	DFF	RFH	DFG
FA		1.000	1.000	1.000	0.975	1.000	0.006*	0.000**	1.000
AAA	0.000**		0.719	1.000	0.124	1.000	0.000**	0.006**	1.000
GA	0.000**	1.000		1.000	1.000	0.436	1.000	0.000**	0.007**
FGA	0.432	0.050	0.606		1.000	1.000	0.165	0.000**	0.079
RFA	1.000	0.000**	0.000**	0.022*		0.069	1.000	0.000**	0.001**
GH	0.001**	1.000	1.000	1.000	0.000**		0.000*	0.016*	1.000
DFF	1.000	0.000**	0.002*	1.000	1.000	0.015*		0.000**	0.000**
RFH	1.000	0.002**	0.048*	1.000	0.342	0.277	1.000		0.804
DFG	0.087	0.328	1.000	1.000	0.003*	1.000	0.902	1.000	
N_2O-N									

* Significant at level $p < 0.05$.
** Significant at level $p < 0.01$.

3.2.3. Dependence on environmental factors

Two of the factors that influence GHG production are soil temperature and moisture (referred to as the groundwater level depth).

Spatial and temporal variations in temperature are shown in Fig. 10. A strong correlation was found between temperature and CO_2 emissions. Coefficients of determination were high in most cases, 0.73 through the entire group (Fig. 11). Likewise, the Spearman rank correlation between the fluxes of CO_2, CH_4, N_2O, depth of the groundwater level and soil temperature (0–10 cm) showed a strong correlation between all of the parameters (Table 5).

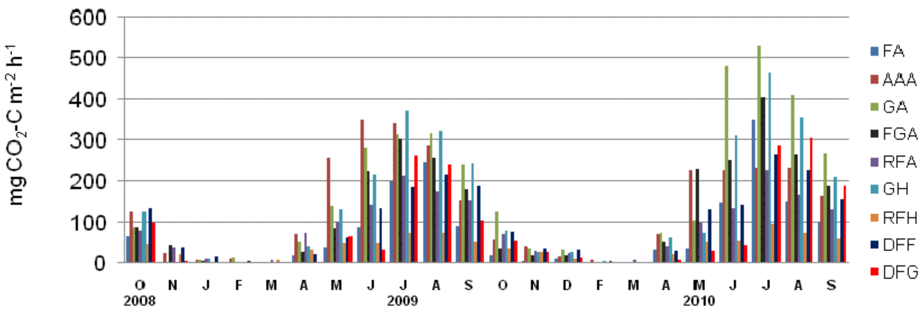
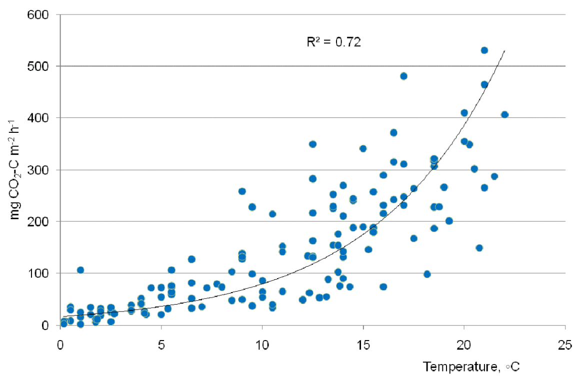


Figure 10. Spatial variation of soil temperature at depth 0–10 cm from 2008–2010. For explanation of abbreviations, see Fig. 3.

A)



B)

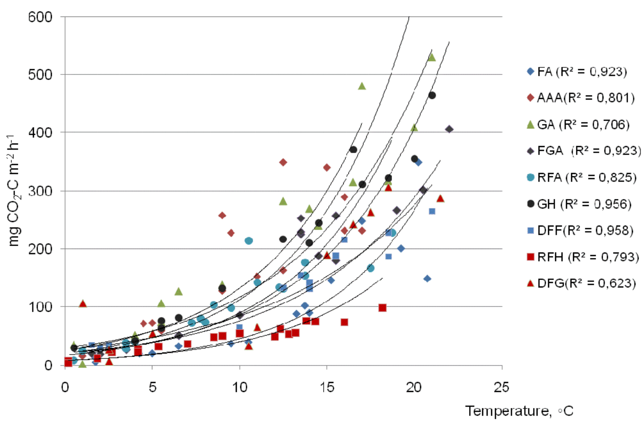


Figure 11. The exponential relation between soil temperature and carbon dioxide flux. A) through all groups; B) in various study site groups. In all cases, $p<0.05$. For abbreviations, see Fig. 3.

Table 5. Spearman rank correlation between the fluxes of CO_2, CH_4, N_2O, the depth of the groundwater level and soil temperature.

Parameter	CO_2-C	N_2O-N	CH_4-C	Soil temperature
N_2O	0.259*			
CH_4-C	–0.531*	–0.378*		
Soil temperature	0.881*	0.272*	–0.363*	
Water level	–0.552*	–0.406*	0.725*	–0.260*

* Significant at level $p < 0.01$.

RDA analysis with forward selection procedure indicated that the variation in GHG fluxes is related to air and soil temperature and site-specific conditions. Air and soil temperature explained 29.1% of overall GHG flux variation, while the group accounted for 35.9% of data variation. Air and soil temperature were most strongly related to CO_2 emission, and temperature correlates somewhat positively with N_2O flux. CH_4 production and oxidation variation were mostly dependent on site-specific conditions. Higher CH_4 fluxes were associated with riparian forests on hydromorphic soils and drained fen grasslands, while CH_4 oxidation is generally higher in riparian forests on automorphic soils and in drained fen forests. The soil potential for CH_4 oxidation is related to water level being higher in the case of lower water level values, and to soil temperature. The model most poorly described the variation in N_2O flux values (Fig. 12).

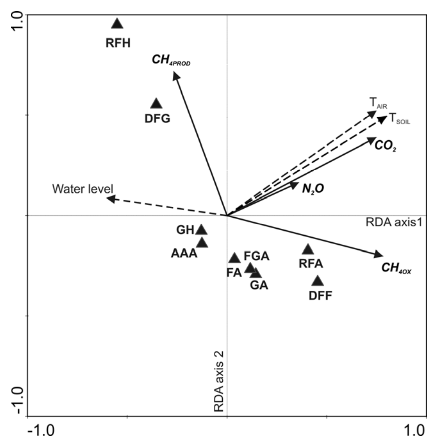


Figure 12. Ordination diagram based on a redundancy analysis of GHG flux data with respect to environmental variables. Dependent variables are indicated by solid arrows, and explanatory environmental variables are indicated by dashed arrows. The qualitative variable group type is indicated by triangles. Variable water level was fitted to the RDA plot as a passive variable. Abbreviations: Tair – air temperature, Tsoil – soil temperature, FA- fertilized arable land on automorphic soils, AAA- abandoned arable land on automorphic soils, GA – grasslands on automorphic soils, FGA – fertilized grasslands on automorphic soils, RFA – riparian forests on automorphic soils, GH- grasslands on hydromorphic soils, RFH- riparian forests on hydromorphic soils, DFF- drained fen forests, DFG – drained fen grasslands.

The results of the RDA analysis suggest that further analysis of microbial community composition, which may be a major factor explaining the variation of GHG emission among study groups, should be undertaken.

3.3. Biophysical factors and greenhouse gas emissions in riparian forests

In the case of the riparian forest soil for the 2008–2009 period, a significant correlation between GHG fluxes, monthly precipitation (mm) and mean monthly air temperature was found (Table 8, Publication III). In Porijõgi, the mean monthly air temperature was significantly correlated with CO_2, CH_4 and N_2 emissions (Spearman Rank Correlation coefficient values were 0.85, 0.58 and 0.54, respectively), whereas in Viiratsi, no significant correlation was found between GHG fluxes and mean monthly air temperature. The monthly precipitation value correlated significantly with the CH_4 fluxes in both study areas (Table 8, Publication III).

Among environmental factors determining the intensity of GHG emissions are soil moisture (referred to as ground water level depth) and soil temperature. This seems to be most relevant in terms of gaseous carbon fluxes (Fig. 6). Considering the Porijõgi and Viiratsi data together, we found that in the case of ground water level deeper than 20 cm from the surface, no significant CH_4 emission appears (Publication III).

Table 6. Spearman Rank Correlation between the fluxes of CO_2, CH_4, N_2, N_2O, monthly precipitation and mean monthly air temperature in Viiratsi (upper part) and Porijõgi (lower part) study sites for the period 2008–2009. * – p<0.05, ** – p<0.01.

			VIIRATSI			
	CO_2	CH_4	N_2	N_2O	Precipitation	Air temperature
CO_2		0.38	0.39*	0.29	0.33	0.12
CH_4	0.61**		0.34	0.12	0.41*	0.17
N_2	0.27	0.21		0.72**	–0.17	0.41
N_2O	0.39*	0.42**	0.06		0.31	0.40
Precipitation	0.16	0.36*	0.00	0.20		0.32
Air temperature	0.85**	0.58**	0.54**	0.28	0.12	
		PORIJÕGI				

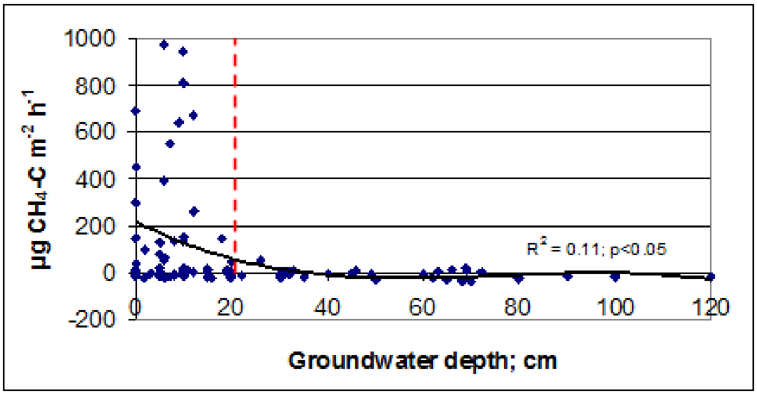


Figure 13. The relation between the depth of groundwater and methane flux in both Porijõgi and Viiratsi study areas. The dashed line indicates that in the case of groundwater depth lower than 0.2 m, most of the CH_4 is oxidized.

3.4. Greenhouse gas emissions from the reedbed

The average CO_2 emission from the reedbed varied from 14.3 to 334 mg CO_2-C m^{-2} h^{-1}. The highest CO_2 emission rates were registered in June in the wet part and in the outflow part of the reedbed (*Fig. 6*, Publication IV). This pattern matches other studies sites in this dissertation, where the flux of CO_2 was highest in June, in the middle of the vegetation period (*Fig. 3*, Publication IV).

In the case of CH_4 emissions, the spatial and temporal variability was the highest. Average CH_4 emission varied from 10.5 in April to 16397 µg CH_4-C m^{-2} h^{-1} in August (Fig. 6, Publication IV). This variability is explained by the differences in temperature and changes in the water table. In April the soil was frozen within the reedbed, in June 0–10 cm above the soil surface and in August 0–10 cm below the soil surface. The fall in the water table in the reedbed during the summer decreased methane emission in both wet and dry reedbeds. In August, during the maximal plant growth in reedbed, the CH_4-C emissions were possibly underestimated, because reed plants may mediate methane fluxes (Altor and Mitsch, 2006; Grünfeld et al., 1999; Duan et al., 2006).

The CH_4-C fluxes measured in the reedbed were in the same range as values gathered in pristine boreal bogs and fens (23–4623 µg CH_4-C m^{-2} h^{-1}; (Salm et al., 2009)), higher than values from drained boreal wetlands (from -83 to 570 µg CH_4-C m^{-2} h^{-1}; (Martikainen et al., 1993), and significantly lower than those registered in wastewater treatment wetlands (27600–528,000 µg CH_4-C m^{-2} h^{-1}; (Tai et al., 2002; Tanner et al., 1997)). Pools in raised bogs can show extremely high CH_4-C emission values in summer (up to 131,875 µg CH_4-C m^{-2} h^{-1}; (Pelletier et al., 2007)). In addition, *Phragmites* stands in boreal lakes (85,900 µg CH_4-C m^{-2} h^{-1}; (Käki et al., 2001)) and on Mollic Gleysols (up to 25,432 µg CH_4-C m^{-2} h^{-1}; (Sommer et al., 2004)), rewetted fens (up to 9000 µg CH_4 m^{-2} h^{-1}; (Augustin et al., 1998)) and small marshes within the agricultural landscape (up to 11,575 μg CH_4-C m^{-2} h^{-1}; (Phillips and Beeri, 2008)) can show high CH_4-C emission values, whereas drained marshes converted to agricultural fields demonstrate significant CH_4 uptake (up to 120 μg CH_4 m^{-2} h^{-1}; (Ding et al., 2004a)).

The average N_2O fluxes from the reedbed were relatively low, varying from –5.0 to 3.7 μg N_2O-N m^{-2} h^{-1}(*Fig. 7*, Publication IV). Teiter and Mander, 2005 and Mander et al. 2008a; Mander et al. 2008b demonstrated a high N_2 emission rates (up to 1200 kg N_2-N ha^{-1} yr^{-1}) and high N_2 : N_2O (up to 2000) ratios in both the HSSF CW and riparian alder forests, which indicates that in these ecosystems the denitrification process lasts to the very end, and not much N_2O is formed.

It is known that the change in wetland water regime significantly influences GHG fluxes, decreasing CH_4 emissions (Harris et al., 1985) and increasing N_2O (Martikainen et al., 1993; Yu et al., 2007) and CO_2 emissions (Van den Pol-van Dasselaar et al., 1998; Kasimir-Klemedtsson et al., 1997). In most cases, a pulsing water regime increases N_2O emissions (Flessa et al., 1998), although there are also contradictory results (Hernandez and Mitsch, 2006). Values of N_2O-N emission from our study are significantly lower than the values observed in various CWs for wastewater treatment (up to 17.000 μg N_2O-N m^{-2} h^{-1}; (Fey et al., 1999; Johansson et al., 2002; Tai et al., 2002; Mander et al., 2003; Xue et al., 1999)), lower than those reported from drained boreal peatlands (2–331 μg N_2O-N m^{-2} h^{-1}; (Salm et al., 2009)) and comparable with flux values reported on pristine boreal peatland ecosystems (1.14–27.4 μg N_2O-N m^{-2} h^{-1}; (Minkkinen et al., 2002; Yu et al., 2007)).

4. CONCLUSIONS

According to the median values derived from the literature analysis, the hot spots of methane are natural peatlands and marshes (106 kg CH_4-C ha^{-1} yr^{-1}), whereas in contrast, nitrous oxide was mostly emitted from drained (partly restored) peatlands and marshes (7.2 and 6.5 kg N_2O-N ha^{-1} yr^{-1} respectively) and also from conventional arable lands on hydromorphic soils (4.5 kg N_2O-N ha^{-1} yr^{-1}), fertilized grasslands (4.2–4.7 kg N_2O-N ha^{-1} yr^{-1}) and coniferous forests on hydromorphic soils (3.8 kg N_2O-N ha^{-1} yr^{-1}).

The measured fluxes of all three gases – CO_2, N_2O and CH_4- varied remarkably on both temporal and spatial scales.

Emissions of CO_2 show different seasonal variations throughout all studied groups, varying from 0 to 530 mg CO_2-C m^{-2} h^{-1}. The Duncan test showed that grassland on automorphic soil had significantly higher emissions than fertilized arable land on automorphic soil, riparian forest on automorphic and hydromorphic soils, drained fen forest and grasslands.

Within gaseous fluxes and environmental parameters, a strong correlation between temperature and CO_2 emissions were found. The production of CO_2 is driven by soil respiration, as soil temperature and moisture (referred to as the groundwater level depth) are the key factors controlling microbial and fungal activity and hence CO_2 production.

The CH_4 fluxes demonstrated higher temporal variability than simultaneously measured CO_2 or N_2O emission rates, varying from –166 to 55745 µg CH_4-C m^{-2} h^{-1}. As a follow-up to the Kruskal-Wallis test, multiple comparisons showed that riparian forests on hydromorphic soils had statistically higher emissions than all of the other groups, except drained fen grassland, which emitted statistically more CH_4 than grassland on automorphic soil, riparian forest on automorphic soil or drained fen forest. Such results matched the literature overview, which demonstrated that emissions from deciduous forests, in this case riparian alder forests, on hydromorphic soils have higher emissions of CH_4 than all other land use types other than peatlands and wetlands. Likewise, the highest fluxes of CH_4 came from den grasslands just before drainage.

There was no clear difference between colder and warmer periods in flux rates of N_2O, which varied from –4.1 to 608 µg N_2O-N m^{-2} h^{-1}. Comparison of N_2O emissions showed that drained fen forests, fertilized arable land and riparian forests on automorphic soils emit significantly more N_2O than abandoned arable land on automorphic soil or grasslands on automorphic or hydromorphic soils. There were also high emissions from drained fen grasslands just after drainage and from fertilized grasslands on automorphic soils directly after fertilization.

According to the literature analysis of peer-reviewed papers indexed by the ISI Web of Science, fluxes of CO_2-C; CH_4-C and N_2O-N in riparian ecosystems vary between 20.6 and 11,400, –5.3 and 420, –1.8 and 6390 kg ha^{-1} yr^{-1} respectively.

The median values of measured cumulative annual fluxes of CO_2-C, CH_4-C, and N_2O-N are 4100, 0.9 and 0.4 kg ha^{-1} yr^{-1} in the less loaded riparian grey alder stand in Porijõgi and 3862, –0.4 and 0.7 kg ha-1 yr^{-1} respectively in the heavily loaded riparian grey alder forest in Viiratsi. Riparian grey alder forests are effective buffering ecosystems with relatively high global warming potential due to high carbon dioxide and nitrous oxide emissions. The higher water table in riparian forests benefits lower global warming potential because of decreasing CO_2 and N_2O emissions; increasing CH_4 emission plays a less significant role.

The average N_2O fluxes from the treatment reedbed varied from –5.0 to 3.7 µg N_2O m^{-2} h^{-1}. Although the spatial-temporal variation of methane emission was great (10.5–16397 µg CH_4 m^{-2} h^{-1}), showing higher values in the inflow part in June, the average emission value of methane is relatively low, and is comparable to natural wetland areas. Unexpectedly, N_2O fluxes from the reedbed were even lower. The denitrification process in this wetland ecosystem can most probably be completed until the last product, N_2, which is harmless to the atmosphere. Soil CO_2 efflux from the reedbed varied from 14.3 to 334 mg CO_2-C m^{-2} h^{-1}, being somewhat higher in the inflow area.

In the case of the riparian forest soils for the 2008–2009 period, a significant correlation between GHG fluxes, monthly precipitation (mm) and mean monthly air temperature was found. In Porijõgi, the mean monthly air temperature was significantly correlated with CO_2, CH_4 and N_2 emissions (Spearman Rank Correlation coefficient values were 0.85, 0.58 and 0.54, respectively), whereas in Viiratsi, no significant correlation was found between GHG fluxes and mean monthly air temperature. The monthly precipitation value correlated significantly with the CH_4 fluxes in both study areas.
Considering the Porijõgi and Viiratsi data together, in the case of ground water level deeper than 20 cm from the surface, no significant CH_4 emission appeared.

The results of the RDA analysis suggest that further analysis of microbial community composition, which may be a major factor explaining the variation of GHG emission among study groups, should be undertaken.

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SUMMARY IN ESTONIAN

Kasvuhoonegaaside emissioon Eesti maastikes

Kliima soojenemine ja seda mõjutavad tegurid on rohkelt uuritud valdkond. Kasvuhoonegaaside emissioonide ja neid mõjutavate protsesside uurimine on laienenud just viimastel aastakümnetel, kuna on välja selgitatud, et kasvuhoonegaaside kontsentratsioonide tõus atmosfääris on oluline põhjus kliima soojenemisel.

Antud doktoritöö käsitleb olemasoleva kirjanduse ülevaadet (Publikatsioon I) ja kolme laiamahulist uurimustööd (Publikatsioonid II, III, IV). Doktoritöö sisuks ja eesmärkideks olid: (1) koostada ja analüüsida kasvuhoonegaaside (CO_2 ja CH_4) emissioone erineva maakasutusega maastikes, tuginedes viimase paarikümne aasta jooksul tehtud uurimustele, (2) mõõta kasvuhoonegaaside (CO_2, CH_4 ja N_2O) emissioone erinevat tüüpi Eesti maastikes, (3) võrrelda saadud tulemusi omavahel ning leida iga gaasi kohta suurimad emiteerijad ehk „kuumad alad", (4) leida seoseid kasvuhoonegaaside emissiooni ja keskkonnaparameetrite vahel. Lisaks uuriti ja analüüsiti reovee puhastussüsteemi järelpuhastina kasutavas roostikus tekkivate kasvuhoonegaaside emissiooni. Käesolevas töös on arvestatud CO_2 emissiooni all eelkõige summaarset taimede ja mulla hingamist. Siinkohal ei arvestata CO_2 taimede poolset sidumist fotosünteesis.

Kirjanduse ülevaade koostati 950 uurimustöö/eksperimendi põhjal, mis kajastasid kasvuhoonegaaside emissioone erinevat tüüpi maastikes (Publikatsioon I). Analüüsis kasutati 165 ISI Web of Science andmebaasis olevaid aastatel 1980 kuni 2009 publitseeritud artikleid. Kuna andmebaas oli mahukas, võimaldas see eristada erinevaid maakasutustüüpe: (1) intensiivselt väetatud põllumaad (2) vähem intensiivselt kasutatud põllumaad (3) intensiivselt majandatavad (väetatud) heinamaad (4) vähem intensiivselt kasutavad heinamaad (5) söötis põllumaad; (6) lehtmetsad; (7) okaspuumetsad; (8) segametsad; (9) madal- ja siirdesoo; (10) madal- ja siirdesoometsad; (11) lammialad; (12) mitmesugused turbaalad (kuivendatud sood, aktiivselt kasutatavad ja taastatud turba kaevandusalad).

Kirjanduse analüüsi tulemused näitavad, et erineva maakasutusega alad võivad metaani emiteerida või hoopis seda siduda. Suurimad metaani emissioonid (kirjanduse analüüsil leitud mediaanväärtuste alusel) leiti eelkõige kuivendatud ja taastatud turbaaladelt (262.8 kg CH_4-C ha^{-1} a^{-1}), millele järgnesid looduslikud märgalad (51,7–200 kg CH_4-C ha^{-1} a^{-1}) ja lehtpuu- metsad hüdromorfsetel muldadel. Suurimad metaani sidujad olid eelkõige just automorfsed metsamullad, varieerudes –3.5 kg CH_4-C ha^{-1} a^{-1} segametsas kuni 1,5 kg CH_4-C ha^{-1} a^{-1} okaspuumetsas.

Suurimad lämmastikdioksiidi mediaanväärtused leiti sarnaselt metaaniga kuivendatud turbaaladelt ning lammialadelt (vastavalt 7,2 ja 6,5 kg N_2O-N ha^{-1} a^{-1}). Samuti olid võrdlemisi kõrged N_2O emissioonid hüdromorfsetelt põllumuldadelt (4,5 kg N_2O-N ha^{-1} a^{-1}) ja väetatud heinamaadelt (4,2–4,7 kg N_2O-N

ha^{-1} a^{-1}). Väiksemad N_2O emissioonid registreeriti automorfsetelt muldadelt: väetamata põllumullad −1,4 kg N_2O-N ha^{-1} a^{-1}, väetamata heinamaad parasniiskel muldadel −0,3 kg N_2O-N ha^{-1} a^{-1} ja metsamullad −0,5 kuni 1,2 kg N_2O-N ha^{-1} a^{-1}.

Tulemused viitavad üldjoontes sellele, et kuivendatud turbaalade taastamine võib küll vähendada CO_2 emissioone, aga seejuures suurenevad nii metaani- kui ka lämmastikdioksiidi emissioonid.

Välitööde raames valiti 13 erineva maakasutusega uurimisala, kus mõõdeti kasvuhoonegaaside emissioone ning uuriti seoseid keskkonnaparameetritega (Publikatsioonid II, III). Parema ülevaate saamiseks rühmitati uurimisalad vastavalt maakasutusele ning mulla struktuurile: automorfsed mullad: 1)intentsiivselt väetatud põllumaa (Rõhu), 2) söötis põllumaa (Rõka), 3) väetatud heinamaa (Sangla), 4) väetamata heinamaa (Pudivere), 5) kaldaäärne lehtpuumets (lepik; Viiratsi, Porijõe ja Rõka); hüdromorfsed mullad: heinamaa (Pudivere), poollooduslik heinamaa (Pudivere) ja kaldaäärne lehtpuumets (lepik; Viiratsi, Porijõe ja Rõka). Lisaks valiti kaks kuivenduse poolt mõjutatud ala: siirdesoomets ja siirdesoo heinamaa.

Mõõdetud kasvuhoonegaaside emissioonid näitasid nii ruumilist kui ka ajalist varieeruvust ja seda kõigi kolme gaasi puhul.

Süsinikdioksiidi emisiooni ajaline muutus oli selgeim, varieerudes vahemikus 0–530 mg CO_2-C m^{-2} h^{-1}, olles suurim soojemal aastaajal, kui taimede kasv oli suurem ja mulla hingamine aktiivsem. Suurimad CO_2 aastased mediaanväärtused olid automorfsetel söötis maa muldadel (8789 kg CO_2-C ha^{-2} a^{-1}), millele järgnesid automorfsed ja hüdromorfsed heinamaamullad (vastavalt 8582 and 6891 kg CO_2-C ha^{-2} a^{-1}). Emissioonide omavahelisel võrdlemisel selgus, et heinamaa automorfses mullas tekib ka statistiliselt rohkem CO_2 kui väetatud automorfsetes põllumuldades, automorfsetes kaldaäärsetes metsamuldades või kuivendatud aladel.

Suurimad CH_4 aastased mediaanväärtused määrati hüdromorfsetes kaldaäärsetes metsamuldades ning kuivendatud siirdesoo heinamaa muldades, vastavalt 15,9 ja 1,4 kg CH_4-C ha^{-2} a^{-1}. Suurimat ajalist varieeruvust näitas kuivendatud sooheinamaa (endisel poldril), kus kõrgemad emissioonid registreeriti kevadise üleujutuse ajast kuni kuivendamiseni, pärast mida emissioon langes mitu suurusjärku ning kuivanud mullakihis algas vastupidiselt CH_4 sidumine. Selline ajaline kulg on seletatav sellega, et keskkonna muutumine anaeroobsest aeroobseseks mõjutab metaani tootvate mikroobide elutegevust ning metaani tootmine metanogeenide poolt asendub metanotroofsete mikroobide poolse metaani tarbimisega.

Selget ajalist trendi dilämmastioksiidi emiteerimisel mullast ei olnud võimalik täheldada, kuna N_2O tekkis mullast nii suvisel, soojal perioodil, kui ka talvisel, külmal perioodil. Kõrgeimad N_2O emissioonid tekkisid väetatud autotroofsest põllumullast, kus aasta keskmine mediaanväärtus oli 1,4 kg N_2O-N ha^{-2} a^{-1}. Samuti olid teistest aladest suuremad N_2O emissioonid automorfsetel kaldaäärsetel metsamuldadel ning kuivendatud siirdesoo metsamuldadel. Alade omavahelisel võrdlemisel selgus, et eelpool mainitud alad emiteerisid ka statistiliselt rohkem N_2O kui ülejäänud uurimisgrupid.

Kasvuhoonegaaside ajaline trend reovee järelpuhastina kasutatavast roostikust oli sarnane teiste uurimisaladega (Publikatsioon IV). Keskmine CO_2 oli 14,3 kuni 334 CO_2-C m^{-2} h^{-1}. Suurima varieeruvusega oli metaan, varieerudes 10,5 kuni 16397 CH_4-C m^{-2} h^{-1}. Sellist suurt kõikumist on võimalik selgitada temperatuuri ja veetasemega. Madalaim väärtus saadi aprillis, kui maapind oli veel külmunud, mistõttu oli ka metaani emissioon madalam ning suurim väärtus saadi suvel, kui veetase oli kõrge. Metaani emissioon langes ka veetaseme langemisega. N_2O emissioonid olid suhteliselt madalad, varieerudes –5 kuni 3,7 µg N_2O-N m^{-2} h^{-1}. Mitmed uurimustööd (Teiter and Mander, 2005 and Mander et al. 2008a) on näidanud väga kõrgeid N_2-N väärtusi (kuni 1200 kg N_2-N ha^{-1} a^{-1}) just tehismärgaladest ning sarnastest süsteemidest, mis võib omakorda tähendada, et sellistes süsteemides toimub denitrifikatsioon lõpuni ning väga palju N_2O ei teki.

Keskkonnaparameetrite ja kasvuhoonegaaside vahelise seose uurimisel leiti kõige tugevam seos CO_2 ja temperatuuri vahel, kus temperatuuri tõustes suurenes CO_2 emissioon ning determinatsioonikordaja läbi kõikide alade oli 0,72. Spearmani astakkorrelatsiooni analüüs näitas, et kõik uuritavad gaasid, mulla temperatuur ja veetase olid omavahel tugevas usaldusväärses seoses. Lisaks uuriti Viiratsi ja Porijõe kaldaäärsete kaitsevööndite puhul ka seoseid meteoroloogiliste näitajatega ning leiti, et Porijõe kaldaäärsest metsamullast tekkivad gaaside emissioonid on usaldusväärses seoses keskmise kuu temperatuuriga, kuid Viiratsi puhul statistiliselt olulist seost temperatuuri ja mõõdetud gaaside vahel ei leitud. Samas korreleerus kuu sademete summa usaldusväärselt kasvuhoonegaaside emissioonidega nii Viiratsi kui ka Porijõe uurimisaladel (Publikatsioon III).

Uurides Porijõe ja Viiratsi kasvuhoonegaaside andmeid koos, leiti, et kui veetase on sügavamal kui 20 cm maapinnast, siis olulist CH_4 emisiooni ei tekkinud ning kogu tekkiv metaan oksüdeeriti metanotroofsete mikroobide poolt.

Täiendavast RDA analüüsist selgus, et kuna kasvuhoonegaaside emissioonide seoseid keskkonnaparameetritega ei olnud võimalik üheselt iseloomustada, on edaspidi vaja täpsemalt uurida mikroobikooslusi, selgitamaks kasvuhoonegaaside ja uurimisalade vahelise varieeruvuse põhjusi.

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