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Snow cover dynamics and its impact on greenhouse gas fluxes in drained peatlands in Estonia

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Snow cover dynamics and its impact on greenhouse gas fluxes in drained peatlands in Estonia

UNIVERSITY OF TARTU
Press

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ORIGINAL PUBLICATIONS

This thesis is based on the following publications which are referred to in the text by Roman numerals:

I Rimkus, E., Briede, A., Jaagus, J., Stonevičius, E., Kilpys, J., **Viru, B.** 2018. Snow-cover regime in Lithuania, Latvia and Estonia and its relationship to climatic and geographical factors in 1961–2015. *Boreal Environment Research 23*: 193–208. https://doi.org/10.1007/s00704-019-03013-5

II **Viru, B.**, Jaagus, J. 2020. Spatio-temporal variability and seasonal dynamics of snow cover regime in Estonia. *Theoretical and Applied Climatology 139*: 759–771. https://doi.org/10.1007/s00704-019-03013-5

III **Viru, B.**, Veber, G., Jaagus, J., Kull, A., Maddison, M., Muhel, M., Espenberg, M., Teemusk, A., Mander, Ü. 2020. Wintertime greenhouse gas fluxes in hemiboreal drained peatlands. *Atmosphere* 11, 731. https://doi:10.3390/atmos11070731

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Author's contribution to the articles denotes: '*' a minor contribution, '**' a moderate contribution, '***' a major contribution.

	Articles		
	I	II	III
Original idea		***	**
Study design	*	***	***
Data processing and analysis	**	***	***
Interpretation of the results	*	***	***
Writing the manuscript		***	***

ABBREVIATIONS

ANOVA	analysis of variance
APEA	abandoned peat extraction area
C	carbon
CH_4	methane
CO_2	carbon dioxide
DB	Downy birch
DOC	dissolved organic carbon
DON	dissolved organic nitrogen
DPF	drained peatland forest
ES	Ess-soo
GHG	greenhouse gas
GWP	global warming potential
IPCC	The Intergovernmental Panel on Climate Change
LA	Laiuse
MK	Mann-Kendall
N	nitrogen
NS	Norway spruce
NAO	North Atlantic oscillation
N_2O	nitrous oxide
ORP	oxidation-reduction potential
PCA	principal component analysis
PVC	polyvinyl chloride
WMO	World Meteorological Organisation

ABSTRACT

Global warming has caused changes in weather conditions in the whole world. The mean winter temperature in northern Europe has increased faster than the global mean. This in turn has effect on snow cover, because warmer winters tend to be rainier and freeze-thaw events are more frequent. Changed wintertime conditions also affect greenhouse gas (GHG) emissions. The objectives of this work were (1) to analyse seasonal, spatial and interannual variability of snow cover and factors having an influence on snow cover in Estonia; (2) to estimate emissions of GHGs CO_2, N_2O and CH_4 in winter in Estonian peat extraction areas and drained peatland forests and (3) to analyse how snow cover influences CO_2, N_2O and CH_4 emissions.

Air temperature is the main factor that determines snow cover duration and snow depth in the Baltic States (Estonia, Latvia, Lithuania). Distance from the Baltic Sea and elevation have the greatest impact on the spatial distribution of snow cover parameters. The decrease in snow cover duration was observed in the entire study area. Yet, there was almost no change in annual maximum snow depth values because the maximum snow depth can be reached during few short-term snowfall events.

Further research was focused on the analysis of snow cover dynamics in Estonia during the period 1950/51–2015/16. The time series of daily snow depth at 22 stations were processed in order to obtain reliable estimates of changes in the snow regime. The spatial variability of snow cover parameters is remarkable across Estonia. The median number of days with snow cover was 112, varying from 61 days in westernmost island Vilsandi to 130 days in south-eastern uplands (Haanja, Otepää) and north-eastern Estonia. On average, the number of days with snow cover has diminished by 27 days since 1951. The shortening of the snow-covered period is mostly occurred due to earlier snow melting in spring.

To estimate wintertime GHG emissions, direct measurements were made using the closed-chamber method in two abandoned peat extraction areas and in two drained peatland forests. The fluxes of greenhouse gases – carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) – varied remarkably in temporal and spatial scales. Median values of CO_2 fluxes were similar between the drained peatland forests (DPFs) and abandoned peat extraction areas (APEAs), though the emissions were a bit higher at the DPFs. Emissions of CO_2 were positively correlated with soil and air temperatures. Negative correlation with snow depth was found in all study sites. The correlation with snow depth was stronger in the DPFs and especially high in the Downy birch forest microsite ($R^2 = –0.75$, $p < 0.001$). Wintertime CO_2 efflux made up 10–25% of the annual release.

In the case of CH_4, a different pattern was seen for APEAs, which mostly were methane emitters, whereas DPFs were mainly methane consumers. At the Laiuse APEA and the Norway spruce DPF site, CH_4 fluxes correlated positively with water table depth. CH_4 flux showed the highest values at a water table > 20cm above the surface. At the APEAs, CH_4 fluxes showed a significant positive

correlation with soil temperature. The fluxes of CH_4 showed negative correlation with snow depth at the Laiuse APEA. Wintertime CH_4 fluxes made up 31–52% of annual release at the APEAs and 33–49% of annual consumption in the drained forests.

Wintertime N_2O fluxes in DPFs were significantly higher than those from the APEAs. Highest N_2O peaks occurred during freeze-thaw events. In the snowy winters, N_2O emissions were especially high in November and March. In cases of deeper snow cover, the emissions were much lower. The highest N_2O emissions were observed at water table depth –30 to –40 cm and at soil temperatures between 0 °C and 8 °C. The fluxes of N_2O had a positive correlation with snow depth at the Ess-soo APEA. Wintertime N_2O release from the drained forests (spruce and birch) accounted for 87% of the total annual emission in both sites.

1. INTRODUCTION

According to the IPCC report, the global average temperature has increased by about 1 °C since 1880 (Stocker *et al*., 2013) and the average rate of increase since 1981 has been more than twice as high as since 1880 (NCEI, 2018). Different climate change scenarios project a warming by 2–5 °C for the end of this century (Stocker *et al*., 2013). Greenhouse gases (GHG) are important components of the Earth´s radiation balance contributing significantly to the global warming. Since the industrial period, the amount of greenhouse gases in the atmosphere has increased due to human activities. According to World Meteorological Organization (WMO) (*WMO Greenhouse Gas Bulletin*, 2019), atmospheric GHG concentrations have increased from 278 ppm in the pre-industrial period to 407.8 ppm for carbon dioxide (CO_2), from 722 to 1869 ppb for methane (CH_4) and from 270 to 331.1 for nitrous oxide (N_2O) in 2018, respectively.

Climate warming will inevitably induce a decrease of seasonal snow cover in the higher latitudes (Brown & Mote, 2009). Snow cover is a very important factor that forms the general character of winter weather conditions. Its persistence significantly changes the surface radiation and heat balances. Due to the high albedo snow reflects most of the incoming solar radiation. Because of high albedo and high radiative power, snow cover significantly cools near-surface air layer. Low temperature, in turn, promotes additional snow accumulation as a result of snowfall. Snow cover has the greatest impact on the Earth´s radiation balance in spring. In the case of a deep snow cover, more heat is reflected during the melting period and springtime air temperature is lower, and vice versa.

Snow cover acts as a very sensitive indicator of climate change. Seasonal snow cover has decreased substantially in the whole world due to the global warming. Ground measurements as well as satellite measurements have shown that the extent of snow cover has decreased significantly (Brown & Robinson, 2011; Estilow *et al*., 2015). The snow cover extent has diminished the most in spring (especially in March and April) (Estilow *et al*., 2015). In the Eurasian mid-latitudes, the duration of snow cover varies from 70 days in southern Siberia to 225 days in the north (Ye & Ellison, 2003). During the past half-century, the end date of snow cover has significantly shifted earlier in the most parts of Eurasia (Zhang & Ma, 2018).

In recent decades, winter precipitation has fallen down more in form of rain than of snow in the south-eastern part of the Baltic Sea region, which has caused the shortening of snow cover duration (Rasmus *et al*., 2015). Snow cover duration has decreased in most of the Baltic Sea region especially due to earlier melting period in spring caused by higher air temperature (Dyrrdal, 2009; Dyrrdal & Vikhamar-Schuler, 2009; Takala *et al*., 2009; Kellomäki *et al*., 2010; Dyrrdal *et al*., 2013).

It has been found earlier, that the mean snow cover duration in Estonia varies from 75 days in the westernmost islands to more than 130 days in the south-east and north-east Estonia (Jaagus, 1997). During the period of 1951–2000, snow cover duration in Estonia diminished by 17–20 days in the hinterland and by 21–36 days on the coastal areas (Jaagus, 2006).

Snow cover significantly influences on wintertime emissions of greenhouse gases CO_2, CH_4 and N_2O (Sommerfeld *et al.*, 1993; Winston *et al.*, 1997; Mast *et al.*, 1998; Alm *et al.*, 1999; Fahnestock *et al.*, 1999; Groffman *et al.*, 2006; Maljanen *et al.*, 2007; Kim *et al.*, 2019). Snow, especially the fresh fluffy snow, has a low thermal conductivity. Therefore, it is a good insulator between overlying air and surface. Temperature under the snow cover is relatively constant even if there are large air temperature fluctuations above the snow. A lack of snow can enlarge soil freezing and depth of frost in soil (Groffman *et al.*, 2001; Kull *et al.*, 2008). More frequent freezing-thawing cycles increase CH_4 and N_2O emissions because soil freezing stresses out fine roots and soil microbial communities. Therefore, increases in freeze events may affect fine root and microbial mortality, cycling and loss of nutrients and soil–atmosphere trace gas fluxes (Groffman *et al.*, 2001). Snow cover may enhance biological production of GHGs in soil or release of trapped gas from deeper layers (Sommerfeld *et al.*, 1993; Zimov *et al.*, 1993a; Melloh & Crill, 1996; Panikov & Dedysh, 2000; Zhang *et al.*, 2005; Kim & Kodama, 2012). Greenhouse gases can be consumed or produced in soils even at temperatures below 0 °C (Zimov, *et al.*, 1993b; Aurela *et al.*, 2002; Groffman *et al.*, 2006).

Wintertime GHG fluxes are an important part of the global carbon and nitrogen budgets. It has been found that wintertime emissions of GHGs accounted for 17–28% of CO_2 (Mast *et al.*, 1998; Alm *et al.*, 1999; Fahnestock *et al.*, 1999; Hao *et al.*, 2006; Kim *et al.*, 2007, 2019), 2–59% of CH_4 (Dise, 1992; Nykänen *et al.*, 1995; Melloh & Crill, 1996; Mast *et al.*, 1998; Alm *et al.*, 1999; Panikov & Dedysh, 2000; Koch *et al.*, 2007; Jiang *et al.*, 2009; Song *et al.*, 2015; Miao *et al.*, 2016) and 2–99% of N_2O from mid- and high-latitude ecosystems throughout the year (Nykänen *et al.*, 1995; Kammann *et al.*, 1998; Alm *et al.*, 1999; Papen & Butterbach- Bahl, 1999; Maljanen *et al.*, 2001, 2004; Kim & Tanaka, 2002; Hao *et al.*, 2006; Jiang *et al.*, 2009; Wagner-Riddle *et al.*, 2017).

Organic soils contribute to the atmospheric GHG concentrations, being either sinks or sources of GHGs. Organic soils are globally extensive carbon and nitrogen stores (Wilson *et al.*, 2016). Peatlands are the largest natural terrestrial carbon store. When peatlands are damaged – for example, drained or used for peat extraction – then they become source of GHG instead of sinks. Disturbed peatlands contribute about 10% of greenhouse gas emissions from the land use sector (Cris *et al.*, 2014). Drainage causes intensive mineralization of organic matter accumulated in peat, which results in significant loss of carbon (C) and plant nutrients, especially nitrogen (N) from the drained area, while CH_4 emissions usually decrease. The large CO_2 emission from drained organic soils is a major concern from the climate change perspective (Mäkiranta *et al.*, 2007; Salm *et al.*, 2012).

Seasonally snow-covered ecosystems are particularly sensitive to climate changes, because the already small climate variability may cause significant changes in snow cover, soil temperature, frost and soil moisture conditions (Stielstra *et al*., 2015; Kotta *et al*., 2018).

The main aim of the thesis was:
to analyse snow cover dynamics in Estonia and its influence on wintertime greenhouse gas emissions.

Specific objectives were:
(1) to analyse seasonal, spatial and interannual variability of snow cover and factors having an influence on snow cover in Estonia;
(2) to estimate emissions of GHGs (CO_2, N_2O and CH_4) during the winter-time in Estonian peat extraction areas and drained peatland forests;
(3) to analyse how snow cover influences CO_2, N_2O and CH_4 emissions.

The hypotheses of the study were:
(1) the duration of snow-covered period has been diminished (especially due to earlier melt in spring). There is considerable territorial variability of snow cover parameters (coastal areas vs hinterland);
(2) winter-time GHG emissions (especially N_2O) have an important part in the annual budget;
(3) without the insulating effect of the snow cover, the winter-time soil temperatures are lower and create more freezing and thawing cycles. This causes increase of N_2O emissions and decrease of CO_2 production (respiration) as compared to the soil with snow cover.

2. MATERIALS AND METHODS

2.1 Snow cover data (Publications I and II)

Snow cover data from Lithuania, Latvia and Estonia was used to analyse changes in the snow cover regime from 1961 to 2015 in the Baltic States. Snow cover data were obtained from 57 meteorological stations: 21 in Estonia, 19 in Latvia and 17 in Lithuania (Fig. 1).

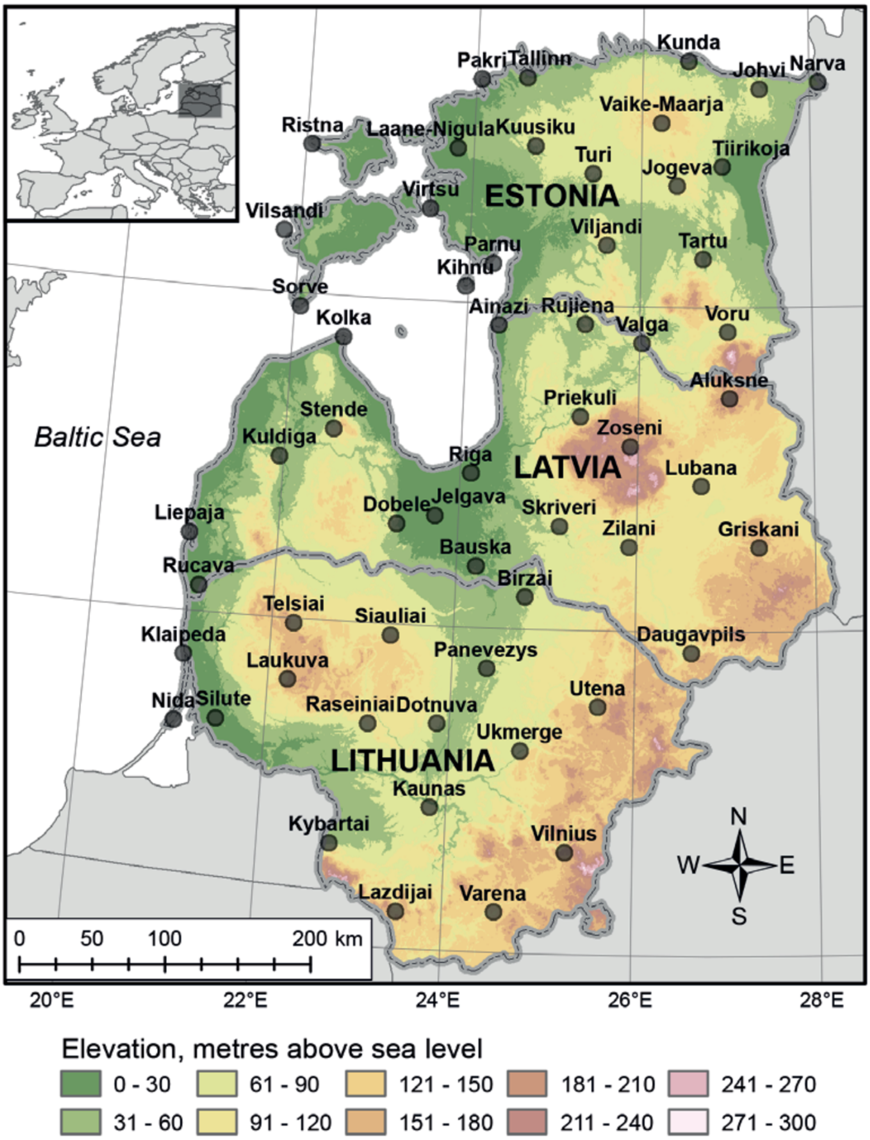

Figure 1. Location of meteorological stations and topography of the study region.

The analysis included snow cover duration (i.e. the number of days with snow cover) and maximum snow depth. In addition, potential factors that may affect snow cover were included. These factors were air temperature, precipitation and geographical factors (latitude, longitude, distance from the sea and elevation). These indicators were calculated for the entire cold season (October–April) and for each separate month (Publication I).

Daily measurements of snow depth at 17 meteorological stations and 5 precipitation stations at different locations in Estonia in 66 winter seasons 1950/51–2015/2016 (months from October to April) were used to study snow cover dynamics in Estonia (Fig. 2). In this study, the following parameters were used: start date and end date of the period with permanent snow cover; snow cover duration, i.e. number of days with snow cover; average and maximum snow depth for the whole winter season and for each month. Time series of these parameters were analysed and territorial analysis was carried out (Publication II).

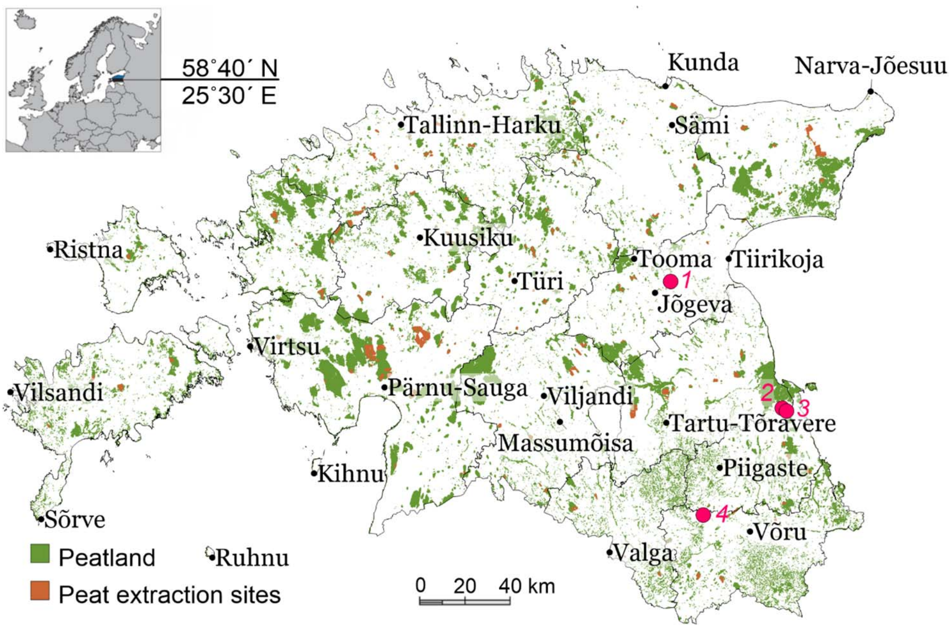

Figure 2. Location of the meteorological stations used for snow cover analysis (black dots) and study sites of greenhouse gas measurements (pink dots) in Estonia. 1 – Laiuse abandoned peat extraction area, 2 – Järvselja spruce drained peatland forest, 3 – Järvselja birch drained peatland forest and 4 – Ess-soo abandoned peat extraction area.

2.2 Fieldwork methodology (Publication III)

The fieldwork was conducted at two abandoned peat extraction areas (APEAs) and two drained peatland forests (DPFs) in eastern and south-eastern Estonia. The locations of the study sites are shown in Figure 2.

2.2.1 Description of study sites

From October 2014 to April 2019, greenhouse gas fluxes were measured (using the static chamber method) at two DPFs in Järvselja, eastern Estonia: a Downy birch (*Betula pubescens* Ehrh.) (DB) forest (58°17′22″ N, 27°19′2″ E) and a Norway spruce (*Picea abies* (L.) H. Karst.) (NS) forest (58°18′11″ N, 27°17′14″ E), both in *Oxalis*-type drained peatlands with two replicate plots. Peat depth was more than 50 cm. In all 4 study plots, drainage work had been carried out in the early 1970s. From October 2017 until April 2019, greenhouse gas fluxes were measured in two APEAs: Ess-soo (ES) and Laiuse (LA). At Ess-soo (57°54′53″ N, 26°41′51″ E) the replicate plots were on adjacent peat fields which were separated by ditches. The peat fields had a slightly convex surface, without trees. Hare's-tail cottongrass (*Eriophorum vaginatum* L.*)* coverage was 10 to 20%. At Laiuse (58°47′26″ N, 26°31′45″ E), the two plots were on adjacent peat fields which were separated by ditches. The most dominant plant species were *E. vaginatum* and bog haircap moss (*Polytrichum strictum* Bridel, J. Bot. (Schrader)). Pine and birch trees grew sparsely at the study site. Both the Ess-soo and Laiuse sites are representative of Estonia's APEAs, and the Norway spruce and Downy birch sites are typical drained forests in Estonia's DPFs.

The top layer of peat had been removed from the peat extraction areas. The remaining peat layer consisted of compacted peat with likely recalcitrant organic carbon. Meanwhile, in the drained forests, only drainage had been conducted and no soil was removed. The most acidic soil occurred in the APEAs (especially the Ess-soo site) while the DPFs were the most neutral (pH values: 2.5, 3.0, 3.8, 4.0; in Ess-soo and Laiuse APEAs and Downy birch and Norway spruce DPFs, respectively). There were also significant differences in C/N ratio, which was considerably higher in the APEAs and lower in the DPFs: 45, 68, 15 and 19 in Ess-soo, Laiuse, Downy birch and Norway spruce sites, respectively. The differences were crucial in formation of the GHG fluxes in the sites.

2.2.2 Sampling and field analyses

The static closed-chamber method (Hutchinson & Livingston, 1993) was used for the measurement of CO_2, CH_4 and N_2O fluxes. For gas measurements, ventilated closed chambers (conical, made of polyvinyl chloride (PVC), height – 50 cm, Ø – 50 cm, volume – 65 L) were placed on the water-filled collars. Collars were pre-installed into the soil in four replicates per plot. In case there was snow cover, the chambers were placed on the snow. Snow was not removed inside the collars and the chambers were sealed as previously described. Gas sampling was carried out twice a month from October to April. Measurements consisted of five gas samples which were collected into previously evacuated 50 ml gas bottles for 1 h (at 0, 15, 30, 45 and 60 min). At each plot during each gas sampling session, the depth of groundwater table (cm) in the observation wells (Ø – 50 mm, up to 1.5 m deep PVC) was determined, and the soil temperature was measured at four depths (10, 20, 30 and 40 cm) by a handheld temperature logger. During each gas sampling session at each plot, groundwater parameters were measured from piezometers (pH, oxygen concentration, redox potential, temperature, electrical conductivity) by a handheld YSI Professional Plus Multiparameter Water Quality Instrument with a Quatro field cable, and air and ground surface temperature by a handheld temperature logger. In addition, at drained forests sites, the soil temperature (at 5 cm depth) was measured with temperature probes and soil volumetric water content was recorded with water content reflectometers at each plot. The automated abiotic data were stored as 1-h averages on a data logger.

2.2.3 Gas analyses

The gas concentrations in the collected samples were determined using a Shimadzu GC-2014 gas chromatography system at the laboratory of the Department of Geography, Institute of Ecology and Earth Sciences, University of Tartu, Estonia (Soosaar *et al*., 2011). Emission rates for one plot were calculated as the average of five subsamples. Gas fluxes were calculated from the linear increase or decrease in gas concentration in each chamber with time, using a linear regression equation (Christensen *et al*., 1995), and were corrected for air temperature according to the ideal gas equation. The following criteria were followed for quality control: R-squared (R^2) p-value < 0.05, $R^2 > 0.77$ (5 data points) or $R^2 > 0.9$ (4 data points) for CO_2 and R^2 p-value < 0.1, $R^2 > 0.65$ (5 data points) or $R^2 > 0.8$ (4 data points) for N_2O and CH_4. To achieve this, one data point was deleted of necessary. In case the difference between the minimum and maximum was smaller than 20 ppm/ppb (ppm applies to CO_2 and ppb to CH_4 and N_2O), the R^2 value was not considered and the data were included in the analysis. In case of snow cover, the volume of chamber was recalculated considering snow depth and density.

2.3 Statistical analyses

2.3.1 Analyses of snow cover data

Snow cover data are non-normally distributed. Therefore, median was used to describe the mean state of snow cover instead of arithmetic average, and quartile range instead of standard deviation to describe its temporal variability. Statistics were found only for these dates when snow cover was observed at least in 50% of winters in the time series. General criteria for determining the period with permanent snow cover are strictly fixed. Snow cover should exist at least on 30 consecutive days. There might be up to 3 days without snow. One snowless day had to be preceded by five snow days, and 2–3 snowless days by at least 10 days with snow cover. If there were two permanent snow cover periods during a single winter between which were up to 5 snowless days, then permanent snow cover did not break. If there were more than 5 snowless days between the two periods then the duration of permanent snow cover period was the sum of the two periods, while the start date of permanent snow cover was considered to be the start date of the first period and the end of the period was the end date of the second period. In the case when snow cover did not exist at least on 30 consecutive days during the winter, then the period with the longest consecutive snow days were used in calculations. If there were two equally long periods, then permanent snow cover period was considered to be the period with higher snow depth. The Mann-Kendall (MK) test has been used to analyse trends in snow cover parameters (Salmi *et al*., 2002; Jaagus, 2006). The slope of a trend line was found by using the Sen's slope estimator. Snow cover parameters were spatially interpolated applying the universal co-kriging method. Surfer 7.0 software was used to create the maps.

The impact of independent geographical variables (i.e. elevation, distance from the sea, longitude and latitude) of the stations on the spatial distribution of snow cover parameters in the Baltic States were also evaluated using a linear multiple regression model in which snow cover parameters were dependent variables and the three geographical factors were independent variables.

2.3.2 Analyses of GHG data

The normality of distributions was checked using the Shapiro–Wilk, Anderson–Darling, Kolmogorov–Smirnov, Lilliefors and Jarque–Bera tests. The distribution of gas data deviated from normal, and hence non-parametric tests were performed. The median, 25% and 75% percentile, and minimum and maximum values of variables are presented. We used the Kruskal–Wallis analysis of variance (ANOVA) test and Dunn's multiple comparison test to check the significance of differences between gas fluxes for different land-use categories and between different years at each study site, and the Spearman rank correlation to analyse the relationship between GHG fluxes and environmental parameters. p values were considered statistically significant after Benjamin–Hochberg correction. Statistical analysis was carried out using STATISTICA and XLSTAT. The level of significance of $p < 0.05$ was accepted in all cases, except in evaluating CH_4 and N_2O flux regressions, when $p < 0.1$ was accepted.

3. RESULTS AND DISCUSSION

3.1 Snow cover regime in the Baltic countries and its relationship to climatic and geographical factors (Publication I)

In the Baltic states area, the temporary snow cover starts to form in the north-eastern part of the region at the beginning of November, in the coastal areas a month later. Generally, permanent snow cover forms 3–4 weeks later. On average, snow depth reaches its maximum in the second half of February or at the beginning of March. About one month later seasonal snow cover disappears, but the interannual variability of the snow cover melt time is very large.

The mean snow cover duration in 1981–2010 was 93 days and it ranged from 56–70 days in the coastal zone in the western part of the territory to more than 130 days in the northeast. The mean snow cover duration in Estonia, Latvia and Lithuania was 98, 94 and 88 days, respectively. Snow cover duration has decreased by an average of 3.3 days per decade. The trend was similar to the findings in previous studies. In the northern hemisphere, snow cover duration has decreased by 5.3 days per decade during 1972–2008 (Choi *et al*., 2010). According to Rasmus *et al.* (2015), the number of snow cover days has decreased by 2.6 days per decade for the whole Baltic Sea drainage basin. Jaagus *et al.* (2017) showed a decreasing trend in snow cover duration in Estonia of 3–4 days per decade. The largest changes were observed in Latvia (–4.2 days per decade) and Lithuania (−4.0 days per decade). The change in Estonia was considerably smaller (–2.7 days per decade).

Although a shortening of snow cover duration was occurred at majority of meteorological stations, a statistically significant change was detected only in 35% of them. Stations with significantly decreasing trends in the snow cover duration were mostly located in the southern part of the study area. The most extensive decrease was observed around the Gulf of Riga and in few stations in Estonia. In areas where mean air temperature in winter is close to 0 °C, even a small change in air temperature can have a huge impact on snow cover. Brown & Mote (2009) have pointed out that largest decreases of snow cover duration were concentrated in a zone where seasonal mean air temperature was in the range of −5° to +5 °C. The average snow cover duration in the analysed area was negatively correlated (r = −0.94) with the average temperature during the period from November to March.

The seasonal maximum snow depth varied from 15–20 cm in the coastal areas and southwestern Lithuania to more than 35 cm in the hilly upland area of the most continental part of Latvia. The average maximum values of snow depth in Estonia and Latvia were similar, 26.7 and 25.7 cm, respectively. The seasonal maximum snow depth in Lithuania was slightly lower. There was no change in maximum snow depth in Baltic States. Exception was Väike-Maarja meteoro-logical station in northern Estonia where the negative change was statistically significant. Decreasing trend of the maximum snow depth has been reported in previous studies, though not always statistically significant, because there is large interannual and decadal variability in snow depth in Baltic countries (Gečaitė & Rimkus, 2010; Bulygina *et al*., 2011; Rasmus *et al*., 2015). Although winter air temperatures have been increased in the region, the thickness of snow cover decreased insignificantly. It is explainable by fact that the annual average maximum snow depth can be the result of few intensive short-time snowfall events. The largest snow-fall events are usually observed when the air temperature is close to 0 °C. During warm winters, when the Baltic Sea is ice-free, the combination of warm sea surface and out-breaks of wintertime cold air may cause intense snowfalls in coastal areas (Savijärvi, 2012). Maximum seasonal snow depth was most closely related ($r = -0.74$, $p < 0.00001$) to the average air temperature during the snow accumulation period (December–February). Generally, there was no relationship between maximum snow depth and precipitation during mild winters, but amount of precipitation was positively correlated with maximum snow depth in cold winters.

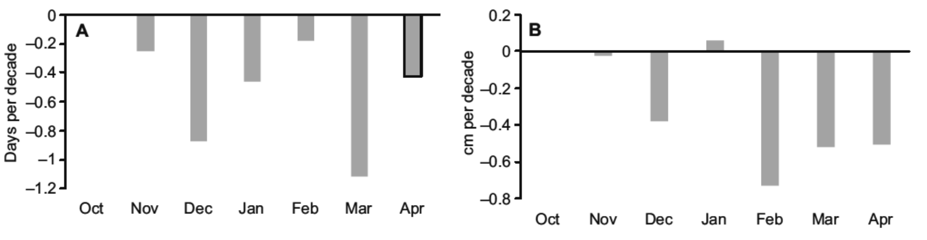

Figure 3. Changes in the (A) snow cover duration and (B) maximum snow depth in different months of the cold season in the Baltic countries during 1961–2015. Statistically significant change is marked with thick line.

The snow cover duration decreased during the whole winter, except October (Fig. 3a). The changes were the largest in March and December, but the only statistically significant trend was recorded in April. Snow depth slightly increased in January, while all changes were negative in December and in the second half of the cold season (Fig. 3b). According to the IPCC report, the snow cover area has decreased in most parts of the northern hemisphere, especially during spring, due to the increase in air temperature (Vaughan *et al*., 2013). The same reason has caused earlier snowmelt and decreased spring snow cover in Baltic Sea region (Rasmus *et al*., 2015). Also snow melt has become shorter and more intense in the northern Eurasia (Bulygina *et al*., 2011). Although the depth of the snow cover decreased in February and March, there were no significant changes in annual maximum snow depth. The largest decrease in the snow cover parameters was observed in March.

Snow cover conditions in Estonia, Latvia and Lithuania are greatly influenced by the Baltic Sea. Snow cover duration has strong correlation with longitude ($r = 0.79$). This relationship is most outstanding in mid-winter with cold temperatures when the thermal contrast between the hinterland and coastal areas is the highest. Elevation is also an important factor, which determines snow conditions. Snow cover forms earlier on uplands, where it is thicker due to less frequent thaws. During mild winters, elevation and longitude have bigger effect on snow cover condition and spatial differences of snow cover parameters are larger. In cold winters, when the sea is frozen, the effect of latitude on snow cover conditions becomes more prominent.

Snow cover parameters are closely related to changes and variations in air temperature, precipitation and large-scale atmospheric circulation. A significant downward regime shift in snow cover duration was detected in 1989 in this study. It has showed previously that there was a regime shift in the temperature, snow cover, precipitation and runoff in Estonia in the winter of 1988–1989 (Jaagus *et al.*, 2017). The period 1988–1989 was related to very high positive values of the NAO index (Rimkus *et al.*, 2014). Since that period wintertime conditions changed from continental to more maritime in the Baltic Sea region (Hagen & Feistel, 2005).

3.2 Snow cover dynamics in Estonia (Publication II)

Snow cover starts to form in the end of autumn and in the beginning of winter seasons. Usually there are several snowy and melting periods before the permanent snow cover forms. Snow depth starts to increase in December (in continental Estonia) and reaches its maximum in the end of February and in the beginning of March. Then it decreases rapidly until the final melt about a month later.

Spatial variability of snow cover duration (number of days with snow cover) is remarkable in the territory of Estonia (Fig. 4). The median number of days with snow cover was 112, varying between 61 days in westernmost island Vilsandi and 130 days in south-eastern uplands. It is consistent with results in previous studies (Jaagus, 1997; Jaagus, 2006; Tooming & Kadaja, 2006). Warming effect of the sea is the main factor that decreases snow cover duration in the coastal regions of Estonia. The interannual variability of snow cover duration was the highest on the islands in western Estonia and the lowest in eastern Estonia. The North Atlantic Oscillation (NAO) index is significantly related to snow conditions in northern Europe (Falarz, 2004; Jaagus *et al.*, 2017). Strong positive NAO is related to intensive westerly circulation with higher temperature and less snow cover. Negative NAO reflects colder winter conditions with a lot of snow.

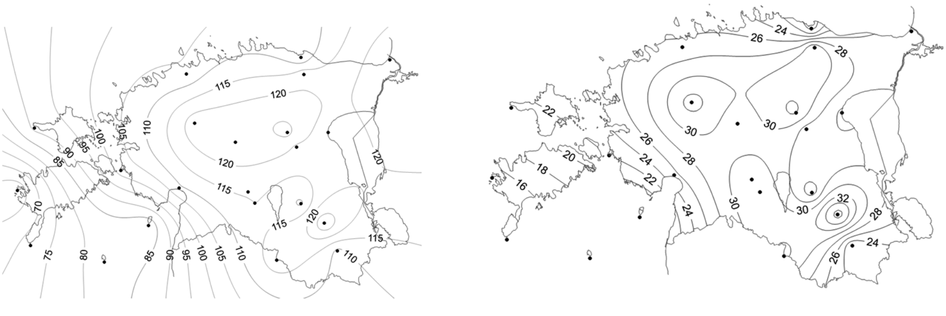

Figure 4. Median snow cover duration (days) (left) and median of annual maximum snow depth (in centimetres) (right) in Estonia in 1951–2016.

As a result of global climate warming, the number of days with snow cover has diminished by 27 days during the study period. Time series on Estonian mean snow cover duration has a statistically significant downward trend (Publication II, Fig.3). Generally, the decrease in snow cover duration was the most remarkable in the central and western part of continental Estonia. Insignificant change is typical for coastal stations in the southwestern islands where snow cover duration has been minimal in Estonia anyway (Fig. 5). Snow cover duration has mainly shortened due to the earlier melting of snow in spring. This change is largely caused due to the general increase in winter temperature and the strengthening of the westerly airflow in winter, especially in February and March (Jaagus, 2006). The decrease in snow cover duration is also observed in the other regions (Falarz, 2004; Choi *et al.*, 2010; Rimkus *et al.*, 2014).

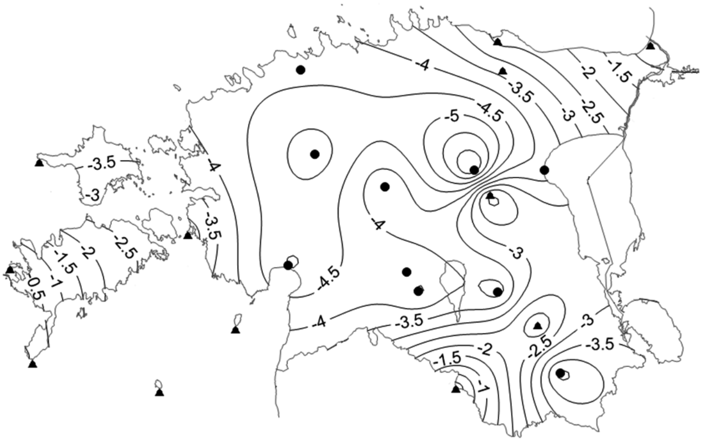

Figure 5. Trend values of snow cover duration (in days per a decade) in 1951–2016. (Round – trend is significant, triangle – no significant trend)

Spatial variability of start and end dates of the permanent snow cover is high in Estonia. Permanent snow cover forms earliest in the Pandivere Upland and north-eastern Estonia and in the south-eastern uplands (Haanja, Otepää). Due to the warming effect of the sea, the permanent snow cover forms the latest on West-Estonian islands and on the western coast. In many winters, there has been no permanent snow cover at all. For example, the permanent snow cover was recorded only on 54.5% of years in Vilsandi, which is the westernmost island. The average start date of the permanent snow cover in the continental Estonia was 19 December varying in stations between 8 and 24 December. The earlier start of the permanent snow cover is related to its lower temporal variability and vice versa (Table 1). Similarly to the start dates of the permanent snow cover, there are large spatial differences also in its end dates (Table 1). The mean of the median dates of stations was 28 March varying in stations between 20 March and 2 April.

The start date of permanent snow cover has not significantly changed during the study period. In general, there is a tendency to a later formation of permanent snow cover, but it was not statistically significant (Table 1). The end date of the permanent snow cover has had a statistically significant negative trend in nearly all stations during the period 1951–2016 (Table 1), i.e. permanent snow cover disappears much earlier. The change has been the highest in south-eastern Estonia, where the end has shifted about one month earlier. In the average, in the continental stations, it has been more than three weeks. The change is largely caused due to the general increase in winter temperature and the strengthening of the westerly airflow in winter, especially in February and March (Jaagus, 2006).

Table 1. Medians, quartile ranges and changes by trend of start and end dates of the period with the permanent snow cover (days). Statistically significant changes on the $p < 0.05$ level are typed in bold

Station	Median start date	Quartile range of start dates	Change by trend of start date	Median end date	Quartile range of end dates	Change by trend of end dates
Jõgeva	12 Dec	33.8	0.0	30 Mar	21.5	–19.3
Kunda	22 Dec	43.0	18.3	24 Mar	22.5	–20.2
Kuusiku	13 Dec	37.5	16.5	1 Apr	22.0	–23.0
Massumõisa	16 Dec	33.3	8.3	29 Mar	23.5	–29.6
Narva	11 Dec	39.8	6.6	29 Mar	24.3	–10.0
Pärnu-Sauga	24 Dec	39.5	13.2	28 Mar	25.3	–22.5
Piigaste	8 Dec	28.8	8.3	1 Apr	22.8	–14.1
Sämi	15 Dec	34.8	2.9	31 Mar	19.8	–10.8
Tallinn-Harku	21 Dec	43.0	8.8	25 Mar	32.8	–13.9
Tartu-Tõravere	20 Dec	41.0	0.0	26 Mar	27.8	–27.2
Tiirikoja	14 Dec	32.3	1.8	27 Mar	30.5	–25.7
Tooma	9 Dec	30.0	17.2	2 Apr	23.8	–21.6
Türi	12 Dec	33.3	13.8	31 Mar	25.0	–19.6
Valga	13 Dec	35.5	0.0	27 Mar	30.3	–24.1
Viljandi	16 Dec	39.0	8.1	30 Mar	21.0	–16.5
Võru	17 Dec	34.5	8.8	20 Mar	35.8	–22.0

Spatial differences in annual maximum snow depth are large in Estonia. The median annual maximum snow depth has been highest in uplands in north-eastern and southern Estonia (on average 40 cm) and lowest on islands in western Estonia (Fig. 4). In general, the interannual variability of the annual maximum snow depth is higher in the Estonian hinterland and lower in coastal areas and on West-Estonian islands. Both the increase and decrease of maximum snow depth occurred. Such spatial differences can be explained by local differences and changes.

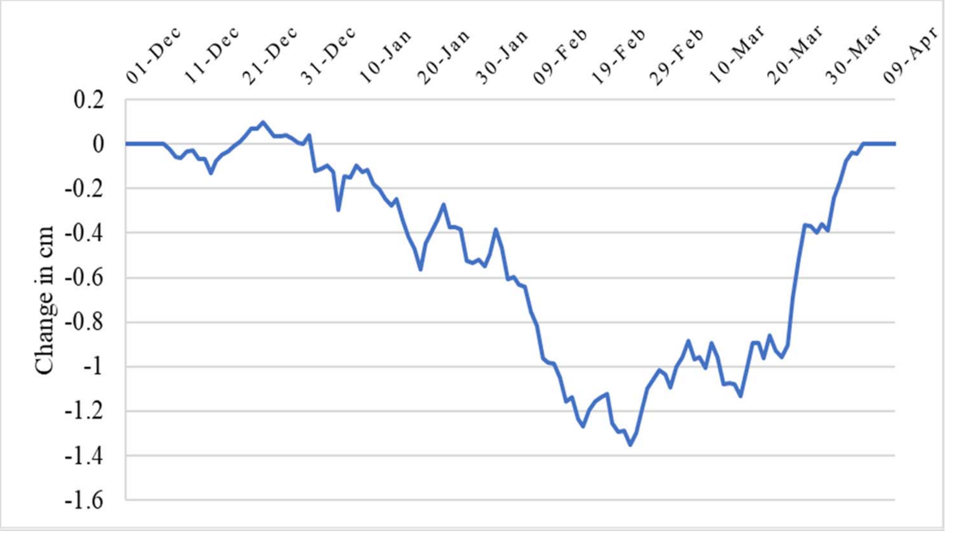

Figure 6. Trend values of daily snow depth in Estonia averaged over the 22 stations (in centimetres) per decade in 1951–2016

Diurnal snow depth trends were found in each station and then the Estonian average was found (Fig. 6). There is a negative trend in time series of daily snow depths from mid-January till mid-March. Decrease in snow depth is the largest in the end of February and in March, which is statistically significant. In the average, snow depth has decreased by 0.5–1.5 cm per decade, i.e. 2–9 cm throughout the whole period (Fig. 6).

3.3 Wintertime greenhouse gas fluxes (Publication III)

3.3.1 PCA analysis and differences in peat layer

Based on the principal component analysis (PCA) according to the soil, water and gas emission characteristics, the APEAs (ES and LA) were under similar conditions and significantly different from peatland forests (DB and NS) ($p < 0.001$ in all comparisons), which were in turn similar to each other (Fig. 7).

The APEAs differed from the forests mainly in higher water table, oxidation-reduction potential (ORP) and dissolved O_2 values, and in lower pH and water electrical conductivity. Different temperatures were strongly negatively related to snow depth, but they showed no significant difference between the studied sites. Considering the gas fluxes, the peatland forests were characterised by higher CO_2-C and N_2O-N, and lower CH_4-C emissions compared to the APEAs.

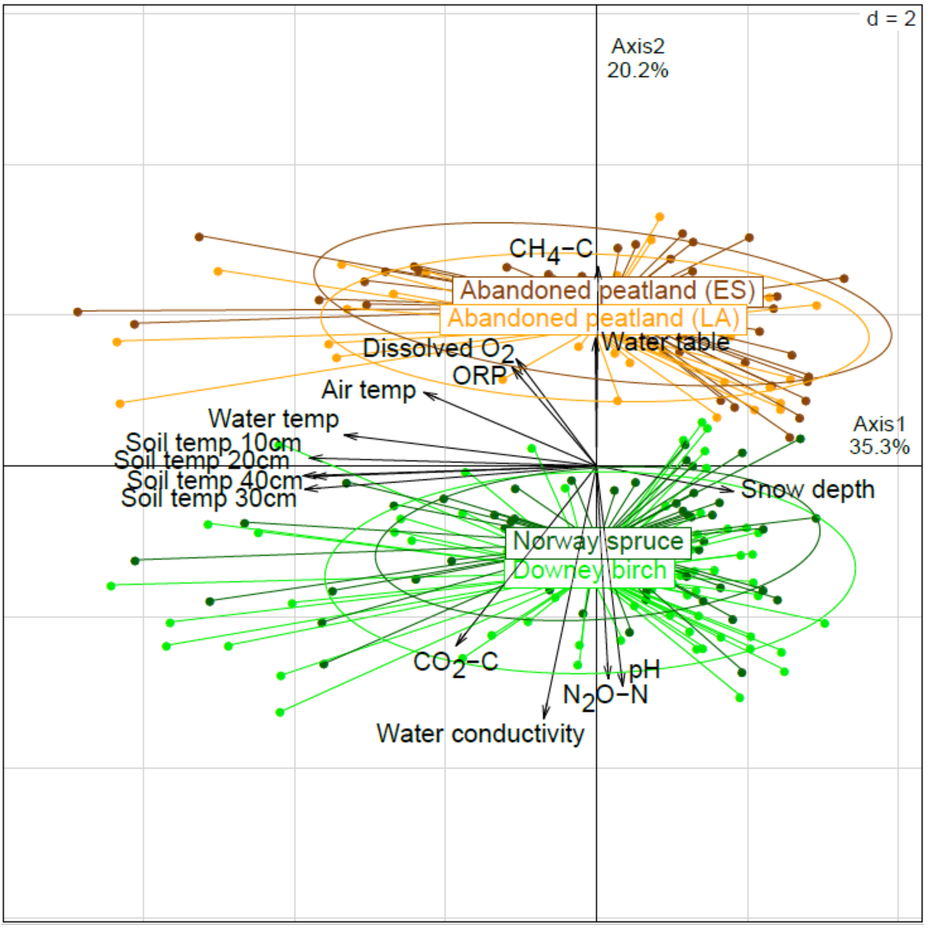

Figure 7. Principal component analysis (PCA) ordination plot with 95% confidence ellipses showing the grouping of studied sites according to environmental characteristics (n = 215). Abbreviations: temp – temperature, ORP – oxidation-reduction potential.

3.3.2 Soil CO_2 flux

Daily average soil flux of carbon dioxide varied between –1.1 and 106 mg CO_2-C m^{-2} h^{-1}. The highest values were measured in October and April and the lowest values were measured in February (Fig. 8). Four study sites did not differ statistically significantly from each other (Kruskal–Wallis ANOVA test, multiple comparison of mean ranks). Median values of CO_2-C fluxes were similar between the DPFs and APEAs, though the emissions were a little higher at the DPFs (Fig. 8). There was no interannual variability in CO_2 fluxes at any study site (Kruskal–Wallis ANOVA test).

Across all study sites the emissions correlated positively with soil temperature at all four depths (10, 20, 30 and 40 cm) (see Fig. 9 for correlation between CO_2 flux and soil temperature at 20 cm depth) and air temperature. In the DPFs, the correlations between CO_2 flux and soil temperature were stronger and especially high in the Norway spruce forest. Our results closely correspond with those of other studies in which CO_2 fluxes were well explained by soil and air temperature (Alm *et al*., 1999; Lohila *et al*., 2007; Huth *et al*., 2012; Kim & Kodama, 2012; Salm *et al*., 2012; Aanderud *et al*., 2013). Lohila *et al*. (2007) have suggested that air temperature is the most important component that influences CO_2 efflux throughout the whole year. Our results showed slightly stronger correlation with upper layer soil temperatures than air temperature.

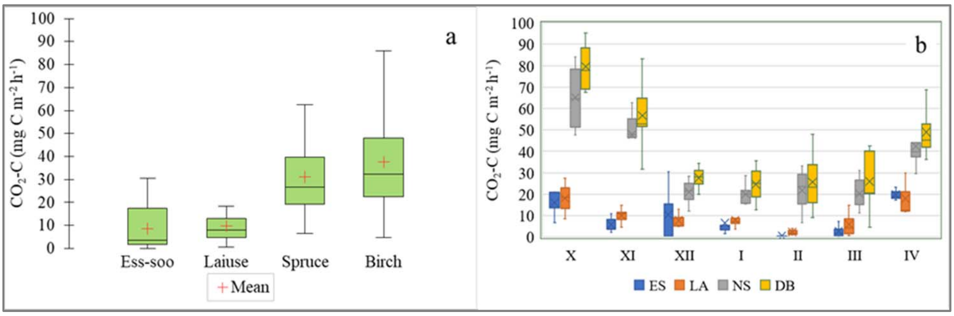

Figure 8. a) Soil CO_2-C flux in abandoned peat extraction areas (Ess-soo (ES) (n = 25) and Laiuse (LA) (n = 25)) and drained peatland forests (Norway spruce (NS) (n = 41) and Downy birch (DB) (n = 41)). b) Average monthly CO_2 emissions during the winter half-year (months on x-axis are monthly from October (X) to March (IV)).

In all areas the correlation was strongest with the topsoil (5–10 cm) temperatures and lower with deeper layer (40 cm) soil temperatures. The top layer (50 cm) of peat has important role in CO_2 production of peatlands, because it has higher substrate quality due to its proximity to organic matter inputs and better access to oxygen (Waddington *et al*., 2001). This may also explain why in the APEAs (ES, LA) CO_2-C emissions were lower in comparison with drained forests – Sphagnum moss had been removed from the sites and the area was covered with sparse vegetation. Though at the LA site there were more vegetation, the average water level was also higher (party flooded in spring during snow melt). Due to the high water level, the circumstances were unfavourable for further peat oxidation, which resulted in lower soil CO_2 efflux compared to the ES site. In both APEAs, the easier biodegradable upper layers of peat had been removed and the remaining deeper layers likely consisted of recalcitrant peat, which was not favourable for CO_2 production (Hilasvuori *et al*., 2013; Mastný *et al*., 2016).

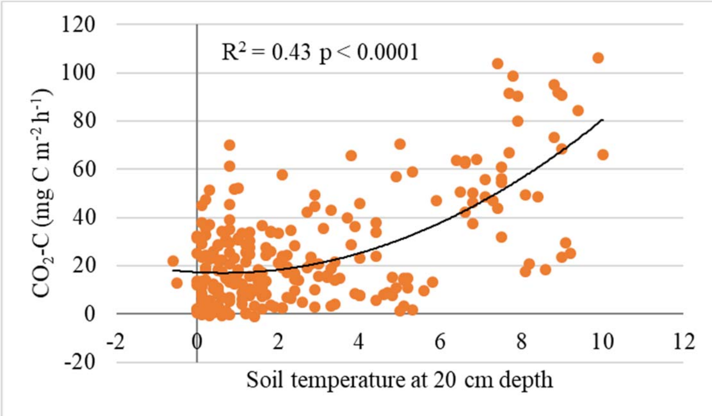

Figure 9. Relationship between wintertime CO_2-C efflux and soil temperature at 20 cm depth at all study sites (n = 246).

Negative correlation with snow depth was found in all study sites (not statistically significant at ES site; Fig. 10). The correlation with snow depth was stronger in the DPFs and especially high in one Downy birch forest microsite (R^2 = –0.75, $p < 0.001$). Soil temperature, which is affected by air-temperature and thickness of snow, regulates the activity of microbes, which determine the amount of CO_2 flux from the soil (Aanderud *et al*., 2013). When snow (especially thick snow) covers the ground, then the soils are warmer and wetter, which can increase heterotrophic respiration. In the case of thin or absent snow cover, the soils could freeze more deeply and result in lower CO_2 emissions. However, thin and sporadic snow cover may cause higher frequency of freeze-thaw events, which may increase the soil dissolved organic carbon (DOC) and dissolved organic nitrogen (DON) concentration (Song *et al*., 2017) and consequently, intensifying the activity of soil decomposers (Sulkava & Huhta, 2003) and winter CO_2 emissions could be larger with a warmer climate (Pihlatie *et al*., 2010). Also, frost damaged fine roots can be a source for fresh available carbon for microorganisms (Comerford *et al*., 2013; Wang *et al*., 2013). Dense root system in drained peatland forest sites is likely a reason why there the CO_2 flux is higher than that in APEAs without any remarkable plant root system.

It has been found that soil moisture is the primary determinant of carbon fluxes in seasonally snow-covered forest ecosystems (Stielstra *et al*., 2015). Nevertheless, we found weak positive correlation between soil moisture and CO_2 flux only in on DPF site (spruce forest).

Average values of cumulative winter half-year soil flux of CO_2-C at the APEAs (ES and LA sites) and drained forests (NS and DB) were 47.8, 41.9, 159.8, and 194.7 g C m^{-2}, respectively. Average winter-day fluxes were 199, 228, 761, 927 mg C m^{-2} d^{-1}. Wintertime CO_2 release from the APEAs (ES and LA sites) and drained forests (NS and DB) on average accounted for 18, 12, 21 and 20% of the total annual emission, respectively. There have been similar findings in earlier works, where wintertime CO_2 emissions has been estimated. In temperate and boreal areas the share of wintertime CO_2 emissions from annual respiration is 10–40% (Oksanen *et al*., 2019). In Artic areas, where the land is covered with snow up to seven months, winter CO_2 emissions are in the range of 10–40% (Kim & Kodama, 2012). Alm *et al*. (1999) found that CO_2 efflux in a drained peatland forest during winter made up 21% of annual release, which is consistent with our results. The variation can be due to different ecosystems and soil types. In our study, the emission and percentage from annual release was higher in DPFs and lower in APEAs with sparse vegetation.

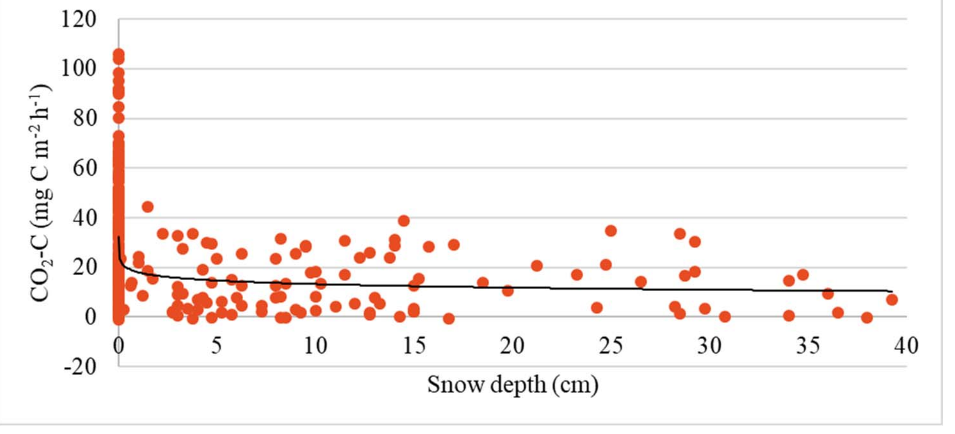

Figure 10. Relationship between CO_2-C efflux and snow depth (cm) at all study sites (n = 236).

3.3.3 CH_4 fluxes

The average CH_4-C emissions varied between –97.7 and 1201.9 µg CH_4-C m^{-2} h^{-1}. There was a significant difference between the APEAs and DPFs (Kruskal–Wallis ANOVA test, multiple comparison of mean ranks), with the highest amounts emitted from the APEAs (Fig. 11). Negative values, which indicate methane consumption, were registered mainly from the DPFs. There was no clear temporal pattern, but in general, the fluxes were higher from October to January and lowest in February and March (Fig. 11). There was no interannual variability in the CH_4 fluxes at the APEAs and Norway spruce site (Kruskal–Wallis ANOVA test). CH_4 fluxes in winters 2014/2015 and 2018/2019 differed statistically significantly at the Downy birch DPF site.

At Laiuse APEA and Norway spruce DPF site, the CH_4 fluxes correlated positively with water table depth. CH_4 flux showed the highest values at a water table > 20cm above the surface. At the APEAs, the fluxes of CH_4 showed significant positive correlation with soil temperature at all four depths (10, 20, 30 and 40 cm). Low soil temperature slowed down CH_4 production in the APEAs which accords with earlier studies (Melloh & Crill, 1996; Alm *et al*., 1999). A part of methane emission in our APEAs was likely caused by the release of capped CH_4 from frozen surface layers: emission peaks occurred mostly when peat surface was slightly frozen. The fluxes were lower in mid-winter when snow cover was the deepest. The fluxes of CH_4 showed negative correlation with snow depth at Laiuse APEA site. In the drained forests, the fluxes of CH_4 were significantly and negatively correlated with water temperature and soil temperature at all four depths (10, 20, 30 and 40 cm).

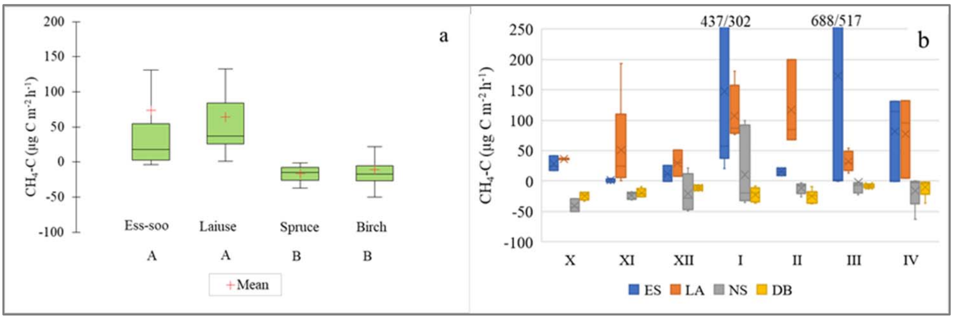

Figure 11. a) CH_4-C emissions from abandoned peat extraction areas (Ess-soo (ES) (n = 25) and Laiuse (LA) (n = 25)) and drained peatland forests (Norway spruce (NS) (n = 41) and Downy birch (DB) (n = 41)). A and B – significantly differing values (Kruskal–Wallis ANOVA test and multiple comparison of mean ranks test). b) cold period CH_4 fluxes; X (October) to IV (April) – months. In both figures, median, 25 and 75% quartile and min/max values are shown.

Average values of cumulative winter half-year soil efflux of CH_4-C in the abandoned peat extraction areas (the ES and LA sites) and drained forests (Spruce and Birch) were 0.25, 0.31, –0.11, and –0.07 g C m^{-2}, respectively. Average winter-day emissions were 1175, 1471, –177, and –140 µg CH_4-C m^{-2} d^{-1}. Wintertime CH_4 release from APEAs (ES and LA site) on average accounted for 31 and 52% of the total annual emission, respectively and wintertime atmospheric CH_4 consumption in the drained forests (Spruce and Birch) on average accounted for 46 and (33%) of the total annual consumption, respectively. Even though in the birch forest methane consumption occurred in most of winters, there was a slight methane release at the beginning and/or the end of winter. Compared to previous studies in peatlands, wintertime CH_4 fluxes rates from APEAs were lower, but share from annual release was twice as high (Dise, 1992). Our drained forests were annual sinks of CH_4. This result corresponds well with earlier studies (Minkkinen *et al.*, 2007; Ojanen *et al.*, 2010). In the forest, water table is relatively low due to canopy interception of precipitation and evapotranspiration (Sarkkola *et al.*, 2010), which may lead to a soil sink of CH_4 (Minkkinen *et al.*, 2007; Ojanen *et al.*, 2010).

3.3.4 N_2O fluxes

Average emissions of N_2O-N varied between –32.2 and 1440.8 µg N_2O-N m^{-2} h^{-1}. The highest peaks of N_2O emission occurred during freeze–thaw events. The months with the highest emissions were November and March (Fig 12). The high N_2O peaks during the freeze-thaw events can be explained by a release of organic carbon as a reluctant for denitrification, by decomposing soil aggregates and killing soil organisms (Oechel *et al.*, 1997; Hao *et al.*, 2006). In the snowy winters, the N_2O emissions were especially high in November and March. In cases of deeper snow cover, the emissions were much lower. In mild winters with a thin snow cover or no snow at all, the emissions were higher also in mid-winter. In contrast, Brooks *et al.*, (1997) found, that wintertime N_2O fluxes were higher in the winters when snow cover formed earlier and lasted longer. Similarly to previous studies (Pärn *et al.*, 2018), our study shows an intermediate water table depth (20–40 cm) at which the emissions were highest (Fig. 13a).

There was a significant difference between the APEAs and DPFs (Kruskal–Wallis ANOVA test; multiple comparison of mean ranks; $p < 0.05$; Fig. 12). N_2O fluxes in the 2014/2015 winter differed significantly from fluxes at the Norway spruce DPF site in the 2017/2018 and 2018/2019 winters (Kruskal–Wallis ANOVA test).

N_2O fluxes were influenced by ecosystem, soil properties and weather. Across all sites, emissions of N_2O correlated negatively with water level depth. Thus, the highest N_2O fluxes were observed at water table depth –30 to –40 cm (Fig. 13a). The N_2O emission showed high values at soil temperatures around 0 °C and 8 °C (Fig 13b). N_2O fluxes at the ES and LA sites were negatively correlated with air temperature. The fluxes of N_2O had positive correlation with snow depth at the Ess-soo APEA site.

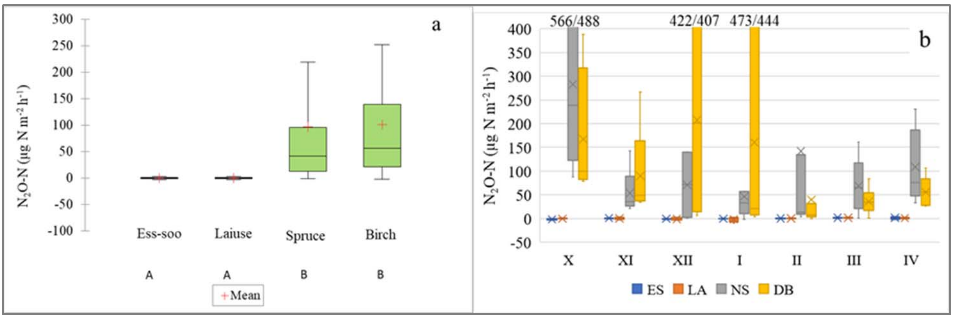

Figure 12. a) N_2O-N emissions from abandoned peat extraction areas (Ess-soo (ES) (n = 25) and Laiuse (LA) (n = 25)) and drained peatland forests (Norway spruce (NS) (n = 41) and Downy birch (DB) (n = 41)). A and B – significantly differing values (Kruskal–Wallis ANOVA test and multiple comparison of mean ranks test). b) cold period N_2O emissions; X (October) to IV (April) – months. In both figures, median, 25 and 75% quartile and min/max values are shown.

Average values of cumulative winter half-year soil efflux of N_2O-N at the APEAs (ES and LA sites) and DPFs (Norway spruce and Downy birch sites) were 0.0005, –0.003, 0.4, and 0.4 g N m^{-2}, respectively. Average winter-day emissions of N_2O 2.38, –12.1, 2000, and 2001 µg N_2O-N m^{-2} d^{-1}. Wintertime N_2O release from the Norway spruce and Downy birch DPF sites accounted for 87 and 87% of the total annual emission, respectively.

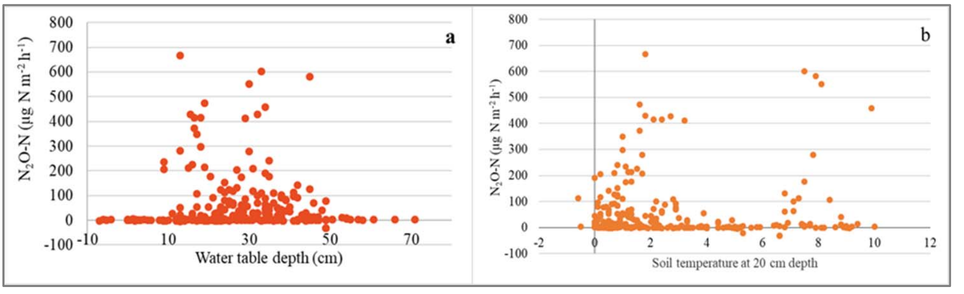

Figure 13. a) relationship between N_2O-N emissions and water table depth (cm) across all study sites. Negative water depth values show flooding. b) relationship between wintertime N_2O-N emissions and soil temperature at 20 cm depth at all study sites.

4. CONCLUSIONS

The air temperature is the most important factor that determines snow cover duration and maximum snow depth in Estonia. The prevailing type of precipitation (i.e., rain or snow) mostly depends on the temperature regime during the cold season. The first hypothesis of this thesis has been proofed: spatial variability of snow cover duration is remarkable in the territory of Estonia. The median number of days with snow cover was 112, varying between 61 days in westernmost island Vilsandi and 130 days in south-eastern uplands. As a consequence of general climate warming, the number of days with snow cover has diminished by 27 days during the study period, especially due to earlier melt in spring. Generally, the decrease in snow cover duration was the most remarkable in the central and western part of continental Estonia. Insignificant change is typical for coastal stations in the southwestern islands where snow cover duration has been minimal in Estonia anyway. As the air temperature continues to rise, winter snow conditions will become more volatile and periods with permanent snow cover will be shorter. On the other hand, the maximum snow depth will increase. This is due to the occurrence of most intense snowfalls when air temperature is slightly below 0 C.

Wintertime CO_2 efflux made up 10–25% of the annual release. Wintertime CH_4 fluxes made up 31–52% of annual release at the APEAs and 33–49% of annual consumption in the drained forests. Wintertime N_2O release from the drained forests (spruce and birch) accounted for 87% of the total annual emission in both sites. Wintertime CO_2 and N_2O fluxes in DPFs were significantly higher than those from the APEAs. Vice versa, mean CH_4 fluxes from DPFs showed cumulative consumption in the drained forests, whereas in the APEAs emission dominated.

Our hypotheses on snow cover effect was only partly supported, showing both a positive and negative impact on different sites and gases. In general, thin and scattered snow cover during the freeze-thaw periods initiates GHG fluxes. In our study, the winters were relatively mild and snow cover was rather thin. Across all study sites CO_2 flux correlated positively with soil, ground and air temperature. A continuous snow depth > 5 cm did not influence CO_2 while under no snow or thin snow fluxes showed the largest variation. Regarding the N_2O and CH_4 fluxes, the correlation with snow depth varied between the gases and sites: in the APEAs and the spruce forest snow cover slightly increased N_2O flux while CH_4 emission in the APEAs showed negative correlation with snow depth. Most likely due to the freeze-thaw effect, the highest N_2O emissions appeared at soil temperatures around 0 °C whereas the fluxes correlated negatively with soil temperature.

Considering the global warming potential (GWP) of the greenhouse gas emissions from the DPFs during the winters, the flux of N_2O (GWP 265 times CO_2 equivalent) was the main component showing 3–6 times higher values than that of the CO_2 flux while the role of CH_4 (GWP 28 times CO_2 equivalent) was of little importance. In the APEAs, CO_2 and CH_4 made up almost equal parts, whereas the impact of N_2O on global warming was minor.

However, in northern regions, milder winters are becoming more frequent due to the climate warming. An increase in freeze–thaw cycles will increase the likelihood of wintertime GHG emissions, especially from DPFs. Groundwater regulation around high levels in these areas would mitigate the emissions.

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SUMMARY IN ESTONIAN

Lumikatte ajalis-ruumiline muutlikkus Eestis ja selle mõju talvisele kasvuhoonegaaside emissioonile jääksoodes ja kõdusoometsades

Maa keskmine temperatuur on tööstusrevolutsioonist kuni tänaseni tõusnud ligikaudu ühe kraadi võrra. Talvise keskmise temperatuuri muutus Baltimaades on olnud suurem kui globaalne keskmine. Erinevate kliimamuutuste stsenaariumite kohaselt tõuseb õhutemperatuur käesoleva sajandi lõpuks 2–5 °C (Stocker *et al.*, 2013). Kasvuhoonegaasid (KHG) on Maa kiirgusbilansi olulised komponendid, andes olulise panuse globaalsesse soojenemisesse. KHG kontsentratsioonid atmosfääris on alates tööstuslikust pöördest inimtegevuse tõttu tõusnud – tasemelt 278 ppm kuni tasemeni 407.8 ppm süsihappegaasi puhul, 722 ppb kuni 1869 ppb metaani puhul ning 270 ppb kuni 331.1 dilämmastikoksiidi puhul (*WMO Greenhouse Gas Bulletin*, 2019).

Kliimasoojenemine on põhjustanud märkimisväärset hooajalise lumikatte vähenemist suurematel laiuskraadidel (Brown & Mote, 2009). Lumikate on oluline tegur, mis määrab ära talvised ilmastikuolud. Lume suure peegeldusvõime tõttu peegeldub suurem osa maale langevast päikesekiirgusest tagasi atmosfääri ning maapinnalähedane õhukiht on jahedam. Madalamad temperatuurid omakorda soodustavad täiendavat lumeakumulatsiooni lumesadude tagajärjel. Soojematel talvedel langevad sademed üha sagedamini vihmana ning sulailmade osakaal suureneb.

Lumikate mõjutab oluliselt talviseid kasvuhoonegaaside (CO_2, CH_4 and N_2O) vooge (Sommerfeld *et al.*, 1993; Winston *et al.*, 1997; Mast *et al.*, 1998; Alm *et al.*, 1999; Fahnestock *et al.*, 1999; Groffman *et al.*, 2006; Maljanen *et al.*, 2007; Kim *et al.*, 2019). Lumi on halva soojusjuhtivusega ning on seetõttu heaks isolaatoriks maapinna ja väliskeskkonna vahel. Lumikatte puudumine soodustab maapinna külmumist (Groffman *et al.*, 2001; Kull *et al.*, 2008). Sagedased külmumis-sulamis tsüklid suurendavad metaani ning dilämmastikoksiidi vooge. Külmumistsüklite sagenemine võib mõjutada juurte ja mikroobide suremust, toitainete ringlust ja kadu mullas ning mulla ja atmosfääri vahelisi gaasivooge (Groffman *et al.*, 2001). Lumekate võib soodustada kasvuhoonegaaside bioloogilist tootmist pinnases või gaasi vabanemist sügavamatest kihtidest (Sommerfeld *et al.*, 1993; Zimov *et al.*, 1993a; Melloh & Crill, 1996; Panikov & Dedysh, 2000; Zhang *et al.*, 2005; Kim & Kodama, 2012). Kasvuhoonegaaside tarbida ja toota mullas on võimalik isegi temperatuuril alla 0 °C (Zimov *et al.*, 1993b; Aurela *et al.*, 2002; Groffman *et al.*, 2006).

Orgaanilistel mullad mõjutavad olulisel määral kasvuhoonegaaside konseratsiooni atmosfääris, olles kas sidujad või emiteerijad. Turbaalad on suurimad süsiniku talletajad maismaal. Kui turbaalasid kuivendatakse või kasutatakse turba kaevandamiseks, siis muutuvad need KHG allikateks. Kuivendamine soodustab turbasse akumuleerunud orgaanilise aine mineraliseerumist, millega kaasnevad suured süsiniku (C) ning lämmastiku kaod, samas CH_4 emissioonid tihtilugu vähenevad. Süsihappegaasi voogude suurenemine kuivendatud orgaanilistest muldadest on eriti suur probleem kliimamuutuste seisukohalt (Mäkiranta *et al.,* 2007; Salm *et al.,* 2012). Turbaalad katavad 22.3% (1 009 101 ha) Eesti territooriumist, jääksood ca 9400 hektarit ning kõdusoo-metsad ligikaudu 14,8% kogu metsamaast.

Hooajaliselt lumega kaetud ökosüsteemid on kliimamuutuste suhtes eriti tundlikud, sest isegi väikesed kliima varieeruvused võivad põhjustada olulisi muutusi lumikattes, mulla temperatuuris, külmumis-sulamistsüklites ning mulla niiskustingimustes (Stielstra *et al.,* 2015; Kotta *et al.,* 2018).

Doktoritöö käsitleb lumikatte dünaamikat Eestis ning lumikatte mõju talvistele kasvuhoonegaaside emissioonidele. Doktoritöö eesmärgid olid: (1) analüüsida lumikatte hooajalist, ruumilist ja aastatevahelist muutlikust ning seda mõjutavaid tegureid Eestis; (2) hinnata kasuhoonegaaside (CO_2, CH_4 and N_2O) talviseid emissioone Eesti jääksoodest ning kuivendatud kõdusoo metsadest; (3) uurida, kuidas lumikate mõjutab talviseid kasvuhoonegaaside (CO_2, CH_4 and N_2O) vooge.

Õhutemperatuur on peamine tegur, mis määrab ära lumikatte kestuse ja lumekihi paksuse Eestis, Lätis ja Leedus. Kaugus Läänemerest ning absoluutne kõrgus on peamised faktorid, mis põhjustavad ruumilisi erinevusi lumikatte parameetrites. Lumikatte kestus on lühenenud kõigis Balti riikides. Samas pole maksimaalne lumekihi paksus uuritava perioodi jooksul praktiliselt muutunud, kuna paks lumikate võib moodustuda ka üksikute intensiivsete lumesadude tagajärjel.

Lumikatte dünaamika uurimiseks Eestis kasutati 22 ilmajaama päevaseid lumikatte andmeid. Territoriaalsed erinevused lumikatte parameetrites Eestis on suured. Selgelt eristuvad Lääne-Eesti saared ning rannikualad ning sisemaa. Lumikattega päevade mediaankeskmine oli 112, varieerudes 61 päevast Vilsandil kuni 130 päevani Kagu-Eesti kõrgustikel. Eesti keskmisena on lumikatte päevade arv vähenenud 27 päeva võrra. Lumikattega perioodi lühenemine on eelkõige tulnud lumikatte varasema sulamise arvelt kevadel.

Välitööde käigus koguti kasvuhoonegaaside proovid kahelt jääksoo alalt (Esssoo ja Laiuse) ning kahelt kõdusoometsa alalt (kuusik, kaasik). CO_2-C emissioonid jääksoodest ja kõdusoometsadest olid sarnased, ehkki veidi kõrgemad olid need kõdusoometsadest. Süsihappegaasi vood korreleerusid positiivselt mulla- ja õhutemperatuuriga. Negatiivne seos lumikatte paksusega leiti kõigil uurimisaladel (polnud statistiliselt oluline Ess-soo alal). Korrelatsioon lumekihi paksusega oli tugevam kõdusoometsades ning eriti tugev kõdusookaasikus (R^2 = –0.75, $p < 0.001$). Talvise aja CO_2 voog moodustas 10–25% aastasest emissioonist.

Kõdusoometsad olid enamasti metaani sidujad ning jääksood metaani emiteerijad. Laiuse ja kuusiku metaaniemissioonid korreleerusid positiivselt veetasemega. Kõrgemad metaaniemissiooni väärtused mõõdeti kõrge veetaseme (> 20 cm) korral. Jääksoodes oli positiivne seos metaaniemissioonide ja mullatemperatuuri vahel. Metaaniemissioon korreleerus negatiivselt lumekihi paksusega Laiuse uurimisalal. Talvised metaanivood moodustasid 31–52% aastasest emissioonist jääksoodes ning 33–49% aastasest tarbimisest kõdusoometsades.

Talvised N_2O vood kõdusoometsadest olid märkimisväärselt kõrgemad jääksoo omadest. Eriti suured olid emissioonid külmumis/sulamisperioodidel. Lumistel talvedel olid N_2O vood märgatavalt kõrgemad novembris ja märtsis ning kesktalvel olid vood märgatavalt madalamad. Kõrgeimad vood esinesid siis, kui veetase oli 30–40 cm allpool maapinda ning temperatuurid olid vahemikus 0 °C kuni 8 °C. N_2O vood korreleerusid positiivselt lumekihi paksusega Ess-soo uurimisalal. Talvised N_2O vood moodustasid 87% aastasest emissioonist nii kõdusookuusikus kui -kaasikus.

Hüpotees lumikatte mõjust kasvuhoonegaaside emissioonile sai osalise kinnituse. Lumikattel oli nii negatiivne kui ka positiivne mõju emissioonidele. Paks lumikate ei mõjutanud oluliselt kasvuhoonegaaside emissioone. Samas puuduva või õhukese lumikatte korral oli emissioonide varieeruvus suur. Dilämmastikoksiidi ja metaani voogude puhul varieerus seos lumekihi paksusega gaasiti ja uurimisalati: jääksoodes ja kõdusookuusikus suurendas lumikate mõningal määral emissioone, samas metaanivoog jääksoodes korreleerus lumekihi paksusega negatiivselt. Eelkõige külmumise/sulamise efekti tõttu esinesid kõrgemad N_2O väärtused siis, kui maapinna temperatuur oli 0 °C juures, kusjuures vood korreleerusid mullatemperatuuriga negatiivselt.

Nii jääksoode edasisel taastamisel kui ka kõdusoometsade majandamisel on kasulik arvestada antud töö tulemusi, vähendamaks kasvuhoonegaaside emissioone atmosfääri. Üheks võimaluseks on reguleerida veetaset ning vältida sagedasi veetaseme kõikumisi.

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