Indicative effects of climate change on groundwater levels in Estonian raised bogs over 50 years

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SUMMARY

Analyses of 50-year (1962–2011) monthly air temperature and precipitation data indicated substantial climate change in the locations of two raised bogs (Linnusaare and Männikjärve) in central-east Estonia. During recent years the cross-year winter air temperature increased by 1.7 ºC, while the cold-season precipitation increased by 4 mm. The fluctuation amplitude of temperature and precipitation values decreased. Snow depth proved to be the most sensitive variable to winter warming, followed by groundwater levels together with mean and maximum soil frosts. Long-term groundwater levels on the domes of the bogs and in the forested/treed lagg areas were 0.3−0.4 m and 0.4−0.8 m below the soil surface, respectively. Warming caused changes in groundwater level amplitude of 3−22 cm in the bog domes and 3−14 cm in the forested lagg zones. The lowest groundwater levels in ridge-pool ecotopes at Männikjärve rose by 6−10 cm (i.e. these ecotopes became wetter); but the incidence of low groundwater levels increased in most ecotopes, indicating a more general trend towards drier conditions in the bog.

KEY WORDS: mire water level, peat frost, peatland, snow cover, winter warming

INTRODUCTION

Groundwater level and its oscillations in patterned bogs (Lode & Leivits 2011) are determined by surface relief and microform types (Mikhaylov *et al*. 2007). The lowest groundwater levels generally occur in tree-colonised parts of the bog, and the highest water levels in treeless open parts (*ibid.*). The groundwater level indicates the water storage capacity in the zone of active groundwater level fluctuation (Bay 1968), and in mires this is an indicator for ecosystem health (Labadz *et al.* 2010).

Primary factors influencing groundwater fluctuations in a bog are precipitation, vegetation, local hydrogeology and type of peat material (Boelter 1964, Bay 1968).

In natural conditions, the general pattern of groundwater level dynamics is rather stable throughout the year. However, any long-term lowering of the groundwater level causes compaction of the overall peat volume, resulting in a subsided bog surface level, which may maintain the groundwater level close to the surface despite the reduced total volume of water stored in the bog massif (Strack *et al.* 2008).

In an undisturbed peat body, the zone of active groundwater level fluctuation has a rapidly changing vertical profile of moisture and aeration conditions, caused by a relatively rapid downward increase in its degree of decomposition (Ivanov 1953, Romanov 1968, Ingram 1978). A transition occurs from high hydraulic conductivity (10^5 m d^{-1} or greater) near the bog surface towards considerably lower values (1–10 m d^{-1}) at a depth of some decimetres below the surface. Thus, the change in hydraulic conductivity in the acrotelm/catotelm boundary layer may be several orders of magnitude (Van der Schaaf 2004). In spite of its shallowness, the upper part of the peat body, i.e. the acrotelm, is the only aquifer in the bog. The thickness of this aquifer is indicated by the lowest water levels (e.g. Ivanov 1981) and it acts as a regulating system for the bog outflow in response to storm water inputs (e.g. Verry *et al*. 1988, Van der Schaaf 1999 cit. Van der Schaaf 2004, Daniels *et al.* 2008).

Acidic and nutrient-poor bogs with patterning formed by pools, hummocks and lawns provide a microform range of groundwater level dynamics that are suitable for specialised plant assemblages dominated by *Sphagnum* mosses (Morgan-Jones *et al.* 2005). Each of the *Sphagnum* species is most successful within a specific range of heights relative to the groundwater level, so that in combination they build microforms where the plant cover shows vertical zonation, at the centimetre scale, of both moss and vascular plant species (Bragg 2002).

Moreover, the different types of microforms composing microtopes have different spatial arrangements and at a larger scale they are a functional part of the hydrological system of the entire mire (Ivanov 1981, Ingram 1987). This results in sensitivity of the bog surface to small changes in wetness, which causes the formation of hummocks and hollows and their associated vegetation, and thus causes the character of microtopes to vary over a long-term time schedule (Bragg 2002).

The groundwater level regime (e.g. Mikhaylov *et al.* 2007) in a patterned bog is the most important driving force of biogeochemical processes in the bog, including carbon cycling and carbon dioxide absorption capacity (Wu & Roulet 2014), which govern dissolved organic carbon (DOC) production and loss in the bog (Fenner *et al*. 2009). Temperature plays a key role in controlling the decomposition rate of peat and is consequently the driver of DOC concentration (*ibid.*). In the short term, lowering of the groundwater level can lead to increased decomposition of the peat matrix, i.e. aerobic DOC production. In the longer term, a lower groundwater level will promote growth of vascular plants over *Sphagnum* spp., leading to a number of biogeochemical changes associated with higher DOC production and corresponding methane and nitrogen gas fluxes (Freeman *et al.* 2001, Toet *et al.* 2006, Fenner *et al*. 2009, Smiljanić *et al.* 2014).

Predicted future changes in annual air temperature and precipitation are likely to cause warmer and wetter winters and springs (Wu & Roulet 2014). Winter is the season that is most affected by climate change at high latitudes, where higher air temperatures can be expected to result in more rain and decreased snow cover (IPCC 2007). The snow-free period in pan-arctic regions has already extended by 3–5 days *per* decade on average, due to earlier spring melt (Tedesco *et al*. 2009). According to predictions, this will result in 40–80 % fewer days of snow cover in Europe by the end of the 21st century (Jylhä *et al*. 2008). Without the insulation of snow, the ground is exposed to freezing and soil frost is able to progress deeper, a phenomenon often referred to as “colder soils in a warmer world” (Groffman *et al*. 2001). This is especially problematic for mire ecosystems, which are considered to be among the most threatened freshwater ecosystems worldwide (IPCC 2014), and particularly for European mires near the southern limit of peat formation (Robroek *et al*. 2013). Therefore, changes in the air temperature regime and other climatological factors may result in shifts in mire ecosystem carbon fluxes (Joosten & Clarke 2002, Aurela *et al*. 2004), infiltration and surface runoff (Quinton *et al*. 2008, Nagare *et al*. 2012) and may also lead to changes in vegetation and microbial community structure (Kreyling & Henry 2011, Templer 2012, Jassey *et al*. 2013).

In this study we had access to 50-year monthly hydrometeorological data from two neighbouring hemi-boreal raised bogs (Linnusaare and Männikjärve). Our research questions were: 1) can we detect any trends that indicate climate change in monitoring data for air temperature, precipitation, soil frost (f), snow depth (S) and groundwater level (GWL) gathered over a period of 50 years? and 2) how do relationships between ground-level variables (i.e. f, S and GWL) on the scale of ecotopes and microforms change through time as a response to changes in climate?

STUDY AREA

In meteorological terms, Estonia is located on the west–east climate gradient (CICERO 2000). Contemporary winter warming is characterised by lowered air pressure and increased cyclonic activity (Jaagus *et al.* 1998, Sepp *et al.* 2005). During the second half of the 20th century, mean annual air temperature in Estonia increased by 1.0–1.7 ºC and precipitation by around 10 % (Jaagus 2006).

The Linnusaare and Männikjärve patterned bogs form part of the 26,600 ha Endla Mire Complex, located in the southernmost part of the Pandivere upland in central-east Estonia (Figure 1). Linnusaare Bog is the largest mire massif (1,250 ha) in the Endla area and since 1997 has been part of the 889 ha Linnusaare Nature Reserve (EELIS 2015). Männikjärve Bog (208 ha) is located to the east of Linnusaare Bog (Kont *et al*. 2007). This eccentric bog developed behind the Tooma moraine hillock in the east and is currently part of the Special Management Zone (EELIS 2015). Both bogs are of limnogeneous origin and contemporary ecotopes contain elongated ridges, pools and hollow microforms up to several metres long.

The Endla area has a long history of drainage. The northern part of Linnusaare Bog was intensively drained in 1935. The lake level in Männikjärve Bog was lowered in 1820–1890 and drainage of the southern and northern surroundings of the bog for forestry occurred in 1910–1914 and 1963–1964. A deep channel was excavated to the south of the bog in 1912. Minor manual peat cutting took place in the eastern part of Männikjärve Bog in the early 20th century (Ilomets *et al.* 2007). Some surface levelling was performed in 1962 and indicated a surface drop of approximately 1 m around the deep channel (EELIS 2015). The main problem for future

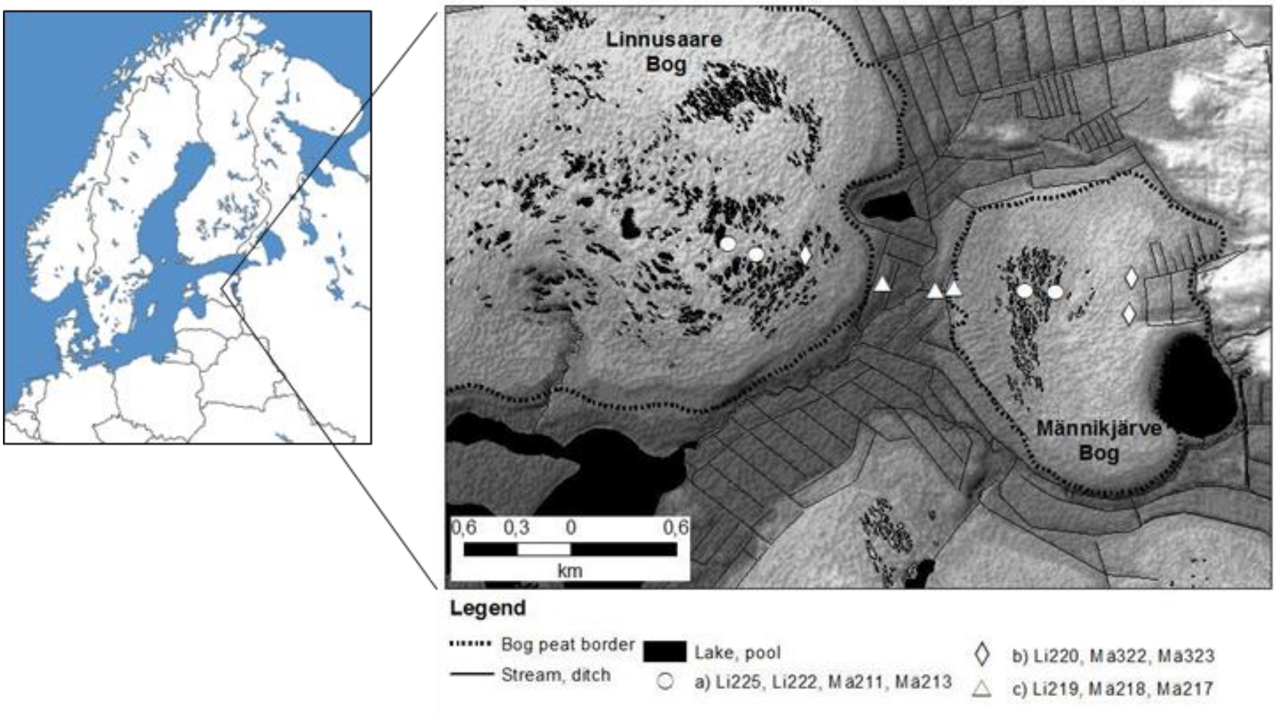

Figure 1. Location of study sites on the digital elevation model of Linnusaare (Li) and Männikjärve (Mä) Bogs (central-east Estonia). The legend lists groundwater (GW) well numbers from west to east. The GW wells are grouped by ecotope type: a) ridge-pool, b) ridge-hollow, c) forested/treed. The digital elevation model was created from LiDAR data scanned by the Estonian Land Board.

development and preservation of the open bog habitats is the intrusion and dispersal of bog pines towards the centres of the bogs which has occurred during the last half-century (e.g. Aaviksoo *et al.* 2008).

METHODS

Field observations

There are currently two (south–north and east–west orientated) hydrological monitoring transects on Männikjärve Bog, which were installed in 1950 within the Tooma Mire Station establishment (Figures 1 and 2). The east–west transect was extended onto Linnusaare Bog at the end of 1970 (Materialy 1973). The mean peat thickness along transects is around 6 m in central parts of the bogs, and 3–4 m in forested laggs. There is an underlying gyttja layer of thickness 1.5–2 m in the laggs, but it does not continue beneath the central parts of the bogs (Materialy 1971). The surroundings of hollows on the eastern part of the dome of Männikjärve Bog have a relatively sparse tree layer and *Sphagnum* has mostly out-competed vascular plants. *Calluna vulgaris* and *Empetrum nigrum* cover the hummocks, while *Scheuzeria palustris* is found in the hollows. In the centre of the bog, *Pinus sylvestris* trees are relatively tall (up to 4–5 m, with crown cover = 0.2) and are abundant on ridges between the pools (Figure 3). Sedges dominate the ground layer. Marginal areas of both bogs are overgrown by 15–20 m high *Pinus sylvestris* resulting from drainage by the ditch network connecting with the Mustjõgi (a natural stream running between the two bog massifs, see Figure 1), and the ground layer is dominated by dwarf shrubs (*Vaccinium myrtillus, Rubus chamaemorus, Empetrum nigrum* and *Andromeda polifolia*). Moving towards the centre of Linnusaare Bog, *Sphagnum*-dominated open bog succeeds the tree-covered marginal area, but in the area of ridge-pool ecotopes *Pinus sylvestris* shows denser and higher growth on the ridges between the pools than in Männikjärve Bog (e.g. Ilomets 1988).

Observations of variables used in this study were based on guidelines for mire stations published in 1972 (Nastavljenie 1972). Meteorological observations, i.e. air temperature and precipitation, were conducted at the bog meteorological (meteo) station in the centre of Männikjärve Bog and at a station on mineral soil located 1 km east-south-east of the meteo station on the bog (Materialy 1980). The observations at the mineral soil meteo station were done year-round,

Figure 2. Ridge-pool ecotope (GW well sites Mä213 and Mä211) at Männikjärve Bog, crossed by the wooden trail of the east–west hydrological transect of Tooma Mire Station, November 2013. Photo: L. Küttim.

Figure 3. North–south oriented and sparsely wooded ridge-pool ecotope on Männikjärve Bog (GW well site Mä211), March 2012. Photo: E. Lode.

while observations in the bog meteo station were limited to May–October. In both stations, air temperature was recorded hourly by thermographs and the amount of precipitation was collected once a day in Tretjakov precipitation buckets.

Ten wooden groundwater (GW) wells were used to measure groundwater levels in Männikjärve and Linnusaare Bogs. The wells were situated in ridge-pool, ridge-hollow, treed/forested ecotopes (Materialy 1966, 1980). Water levels were measured manually every third day all year round.

Soil frost (f) and snow depth (S) were measured only in Männikjärve Bog. These measurements were carried out in depression (D) and hummock (H) microforms of treed, ridge-pool and ridge-hollow ecotopes. One set of f and S data for the ridge-pool ecotope belonged to the bog pool measurements (hereafter referred to as D_pool). Frost depth in the peat body was determined using PVC gauges with smaller rubber tubes inside, filled with distilled water and capped with a rubber bung. Snow depth was measured manually with a stick close to the soil frost measuring sites (Materialy 1966). Measurements of frost and snow depths were made at least three times *per* month, i.e. every ten days, and every five days at the onset and end of winter.

Data handling

The 50-year monthly data (January 1962 to December 2011) used in this study were recorded at the Tooma Mire Station (Estonian Environmental Agency (KAUR)). Digital data were available from 1998. We digitised older data from hydrological yearbooks and observation diaries of the mire station. Data were compiled for the following variables: a) air temperature (T_{air} (°C)) and precipitation (P (mm)), b) soil frost (f_{mean} and f_{max} (cm below bog soil surface (BSS)) and snow depth (S_{mean} (cm)), c) GWL (cm BSS).

In order to address our research questions we performed: a) 50-year trend analyses and compilations of the corresponding annual and seasonal statistics with probability and frequency analyses; and b) multiple clustering and regression analyses.

We divided each calendar year into two seasons on the basis of the T_{air} data. The warm season had mean monthly $T_{air} \geq 5$ °C, i.e. it included months without soil frost and snow on the bog monitoring sites. The remaining months of the year were defined as the cold season. There were 26 years (i.e. 54 %) with six warm months (starting in May) and 14 years with five warm months (starting in May). The longest warm seasons (seven months) were recorded in 1989 and 2007 (starting in April), while the shortest (four months) were in 1971, 1975 and 1988 (starting in June). In 1964, 1965 and 1966, the warm season also started in June but lasted for five months.

Since the T_{air} and P observations on the bog were made for only a limited period during each year, we used the T_{air} and P data from the Tooma mineral soil meteo-square. Our earlier analyses showed a high correlation of T_{air} and P data between the two meteo stations (r = 0.98 and 0.99; Lode & Endjärv 2003).

Simple linear trend analysis was applied for all data, while 12-month moving averages were used for T_{air}, P and GWL data to smooth out seasonal variations in the datasets. The coefficient of variation relating to the long-term mean, k_x, for the smoothed data was calculated as follows:

$$k_x = x_j / x_o \qquad [1]$$

where x_j represents a single value in the dataset and x_o is the mean of the whole dataset.

We distinguished two observation periods to simplify the climatological effects study: Period I (1962–1988) and Period II (1989–2011). These periods were temporally separated at the trend line crossing point $k_T = 1.0$ of the T_{air} data.

Due to the seasonal and cross-year character of f and S events, the trends and statistical analyses for these variables were applied to the winter season 1962/1963–2010/2011. Comparative statistics were also calculated for corresponding average winter season periods I (62/1963–87/1988) and II (88/1989–10/2011). All digitised f and S data were converted to mean monthly levels.

The *JMP Pro 12.0.1* software modules (SAS Institute Inc., Cary, NC, USA) were used for statistical and frequency analyses, visualisation of corresponding probability curves, constellation plots and multiple regression maps.

RESULTS

Air temperature and precipitation

The 50-year monthly means of T_{air} and P recorded at Tooma Mire Station were 4.9 °C and 57 mm, respectively (Table 1, Figure 4). Comparing Period II with Period I, T_{air} increased by 1.3 °C and P increased by only 1 mm. The rise in T_{air} for the cold season was 1.1 °C, and for the warm season it was 0.4 °C. The cold-season P increased by 4 mm and the warm-season P decreased by 4 mm. The associated cold-season warming was considerable, with 17 % decrease in T_{air} variation, while T_{air} variation increased by 8 % in the warm season. No change in the variation of cold-season P was encountered, but P increased by 11 % in the warm season (Table 1).

Table 1. Statistics of long-term monthly air temperature (T_{air}) and precipitation (P) data recorded at the Tooma mineral soil meteo station together with corresponding Period I and Period II statistics. In this Table and later: *Std.Dev. = standard deviation, **n = length of the data range, ***Max, Min = maximum and minimum, respectively.

Moments	Annual		Cold season		Warm season	
	T_{air} (°C)	P (mm)	T_{air} (°C)	P (mm)	T_{air} (°C)	P (mm)
Mean (1962-2011)	4.9	57	-1.9	44	12.7	71
*Std.Dev.	8.6	34	5.1	23	3.9	38
**n	599	600	313	314	280	280
***Max	22.2	225	12.8	124	22.2	225
Median	4.9	51	-1.7	42	13.6	67
***Min	-16.4	0	-16.4	0	1.1	0
I mean (1962–1988)	4.3	56	-2.4	42	12.5	73
II mean (1989–2011)	5.6	57	-1.3	46	12.9	69
±differences	+1.3	+1	+1.1	+4	+0.4	-4
I Std.Dev.	8.8	33	5.4	23	3.7	36
II Std.Dev.	8.3	34	4.5	23	4.0	40

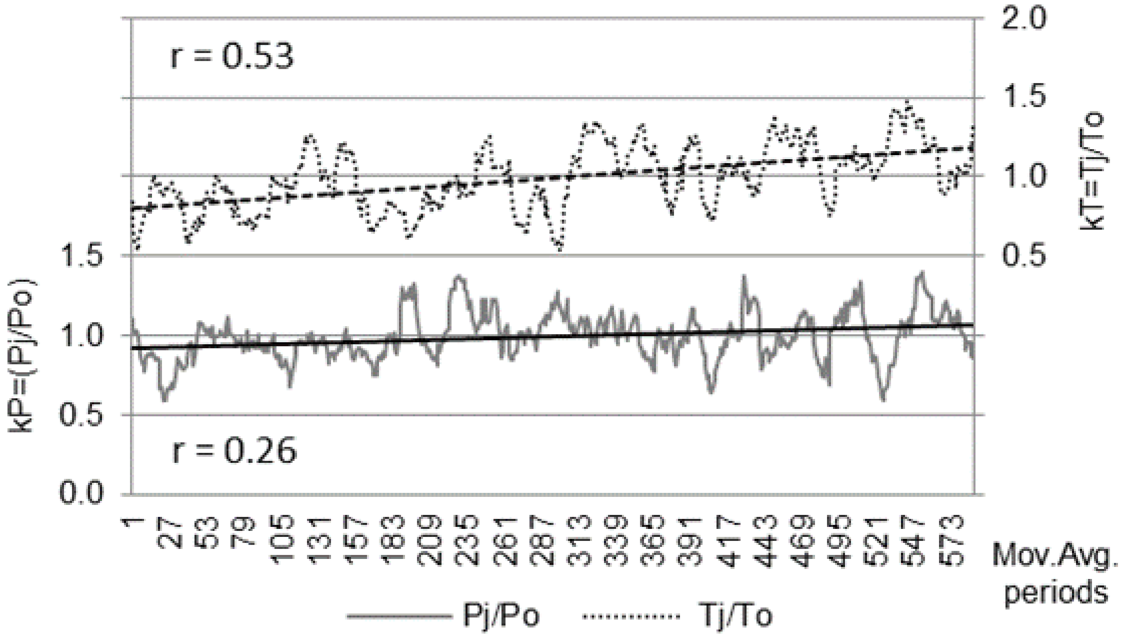

Figure 4. Linear trends in the variation coefficients of air temperature and precipitation (k_T and k_P, respectively) for 12-month moving average (Mov.Avg.) periods during the 50-year study period (see Equation 1). In this Figure and later, *r* = the regression value.

Probability plots (PBPs) of Period II T_{air} showed a significant cold-season T_{air} rise within the 0.0–0.6 quantile interval and a slight T_{air} decline within the 0.6–1.0 interval. No substantial changes in the warm-season T_{air} PBPs occurred (Figure 5). At the same time, the PBP of the cold-season P data was slightly elevated above that for almost the whole of Period I, while the warm-season P increased remarkably within the 0.9–1.0 quantile interval and was lowered within the 0.0–0.6 quantile interval. The difference between the warm-season and cold-season P data showed a steady increase toward higher quantiles, with the difference amounting to approximately 100 mm.

The frequency analyses showed that the highest cold-season T_{air} frequency of both periods occurred within the (-5)–0 °C T_{air} interval (Period I and II frequencies = 36 % and 45 %, respectively). In the warm season the frequency within the 10–15 °C interval was 41–42 %. During Period II, the cold-season T_{air} frequency within the (-5)–0 °C interval increased by 25 % with a simultaneous T_{air} frequency reduction in the lower or colder (-20)–(-5) °C interval. The warm-period T_{air} frequency within the 5–15 °C interval decreased by 2–13 % with a simultaneous increment within the warmer 15–25 °C interval (Figure A1, Appendix). The highest cold- and warm-season P frequencies of Period I occurred within the 30–60 mm P interval (frequencies = 47 % and 33%, respectively). During Period II, the cold-season P frequency amplitude shortened by extreme values of 120–150 mm P interval although there were no changes relating to the prevailing 30–60 mm P frequency interval at the same time. The warm-season P frequency decreased by 6 % within the prevailing P interval together with a simultaneous P frequency amplitude enlargement to 0–240 mm (Figure A1, Table 1).

Soil frost and snow depth

The 50-year soil frost means (f_{mean}, f_{max}) over the average winter months were 14 and 25 cm BSS (Table 2). During the same period the average monthly air temperature was -2.9 °C, the mean for the coldest month was -8.3 °C, and snow depth was 16 cm. The reductions in f_{mean} and f_{max} during Period II were, correspondingly, 1 cm and 3 cm, while the increases in $T_{air\ mean}$ and $T_{air\ min}$ were 1.7 and 2.4 °C, respectively.

The 50-year snow depth values (S_{mean}) showed 10-year, 18-year and 21-year cyclical patterns (Figure 6). However, the overall trendline of S_{mean} is almost horizontal, mainly due to high values at the end of the study period. Therefore, the S_{mean} in Period II was only 3 cm lower than in Period I (Table 2).

The 50-year PBPs of f_{mean} and f_{max} values for D and H microforms of different ecotopes showed continuously higher values (i.e. thicker frost layer) in the H microform of the ridge-hollow ecotope against the smaller values (i.e. thinner frost layer) in the D microform of the treed ecotope (Figure 7). The long-term PBPs of the ice thickness on frozen pools were the lowest, i.e. the frost layer was the thickest. The thinner frost layer in the forest D microform was accompanied by the lowest snow depths on the same microform. Herewith, the plots of f_{max} values formed the most dispersed graph pattern, and plots of S_{mean} values the most convergent.

As a rule, Period II plots showed diminished f_{mean} and S_{mean} values for both H and D microforms of different ecotopes, except for the H microform in the ridge-hollow ecotope, which had continuously increasing f_{mean} values (i.e. fall within the 0.0–0.7 quantile interval). S_{mean} values of Period II decreased more strongly in treed microforms, followed by the ridge-hollow and ridge-pool microforms (Figure 8).

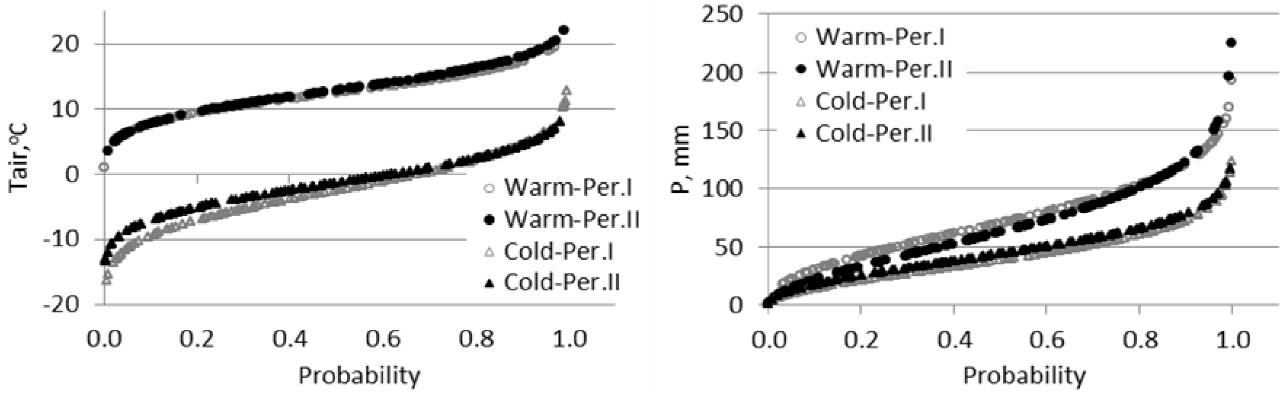

Figure 5. Probability plots of air temperature (T_{air}) and precipitation (P) for the warm and cold seasons of Periods I and II.

Table 2. Statistics of long-term monthly mean and maximum of soil frost (f_{mean} and f_{max}, respectively), snow depth (S_{mean}), air temperature ($T_{air\ mean}$) and mean of the coldest month ($T_{air\ min}$) for average winter seasons (Periods I and II, respectively).

	Moments	Variables				
		*f (cm)		S_{mean} (cm)	T_{air} (°C)	
		f_{mean}	f_{max}		$T_{air\ mean}$	$T_{air\ min}$
Period I	Mean (63/1964-10/2011)	-14	-25	16	-2.9	-8.3
	Std.Dev.	5.3	7.8	8.0	2.1	3.7
	n	50	50	50	47	48
	Max	-26	-51	42	-8.9	-16.4
	Median	-15	-24	15	-2.7	-8.3
	Min	-4	-9	3	4.3	-1.5
Period II	I mean (63/1964-87/1988)	-15	-26	17	-3.7	-9.5
	II mean (88/1989-10/2011)	-14	-23	14	-2.0	-7.1
	± differences	+1	+3	-3	+1.7	+2.4
	I Std.Dev.	4.6	7.6	7.2	1.9	3.6
	II Std.Dev.	6.0	8.1	9.0	2.0	3.4

*f values below the surface, in this table and later, indicated by “-”.

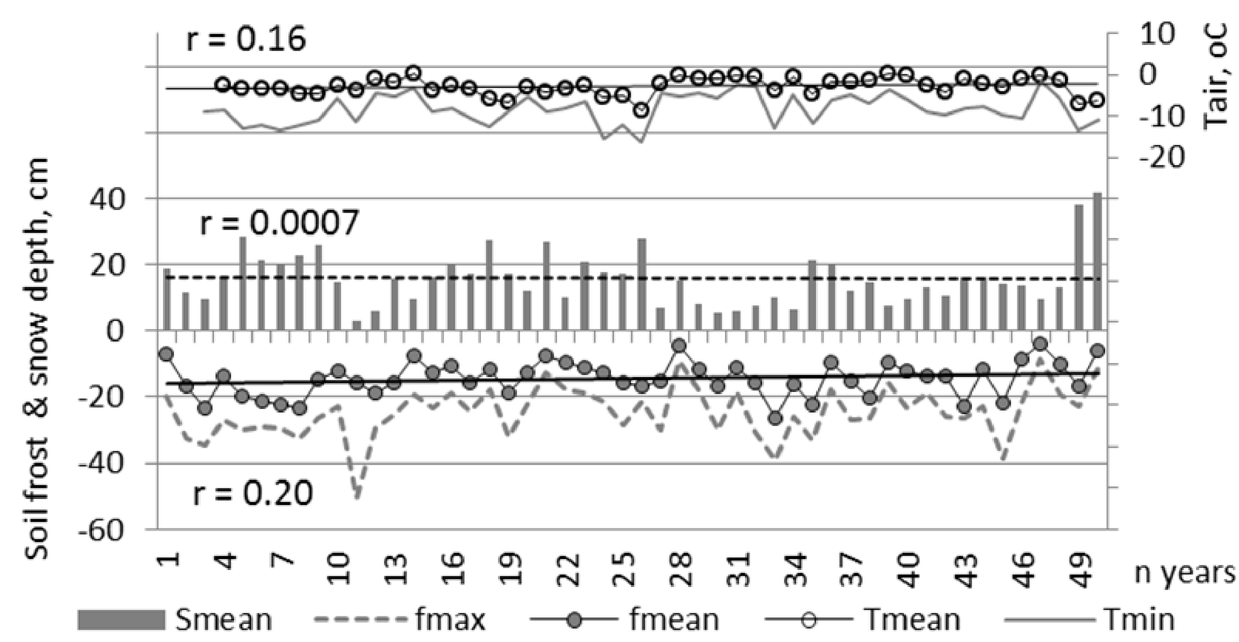

Figure 6. Linear trends of soil frost (f_{mean}, f_{max}), snow depth (S_{mean}) and air temperature (T_{mean}, T_{min}) for the average winter months.

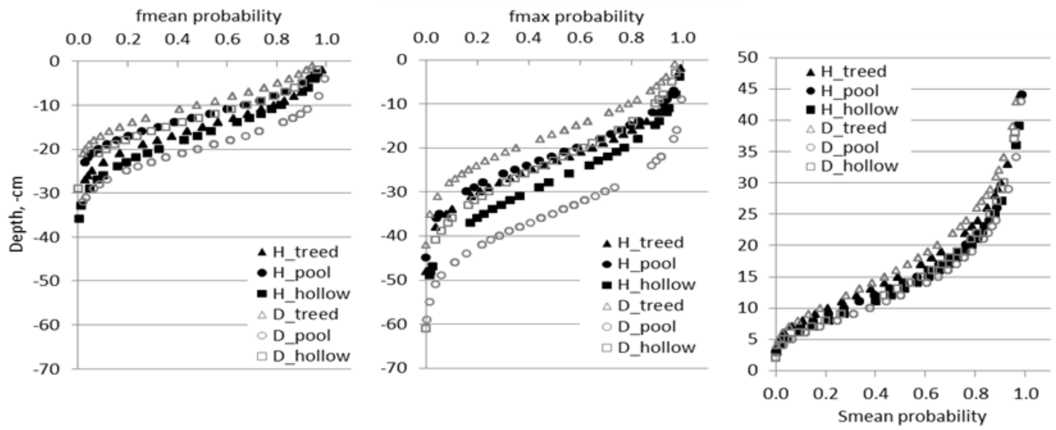

Figure 7. PBPs of the 50-year soil frost (f_{mean}, f_{max}) and snow depth (S_{mean}) values recorded at hummock (H) and depression (D) microforms of the Männikjärve treed, ridge-pool and ridge-hollow ecotopes.

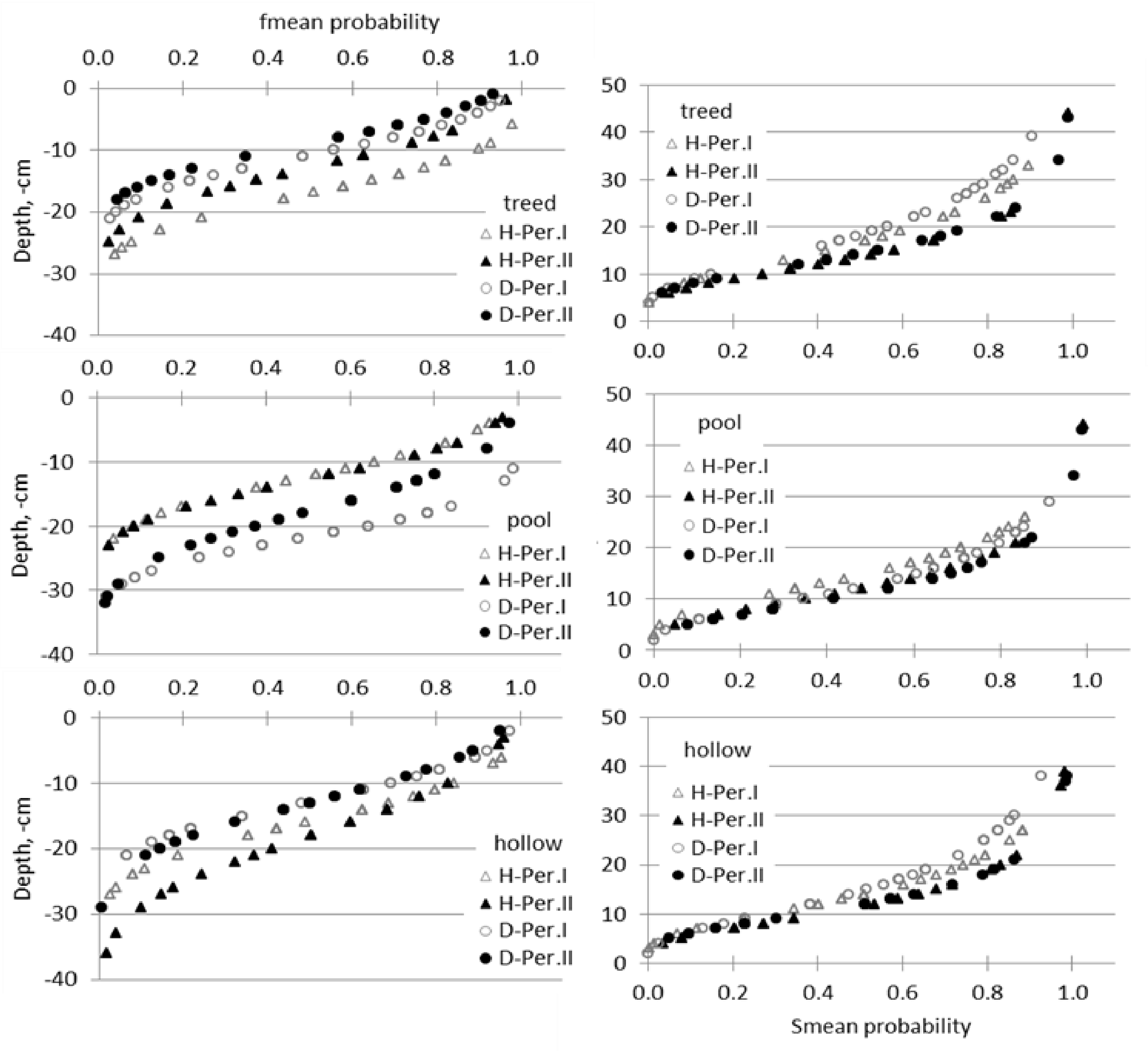

Figure 8. PBPs of the Period I (Per.I) and Period II (Per.II) soil frost (f_{mean}) and snow depth (S_{mean}) values recorded at hummock (H) and depression (D) microforms of the Männikjärve treed, ridge-pool and ridge-hollow ecotopes.

Groundwater levels

The 50-year monthly means of the ridge-pool and ridge-hollow GWLs varied between 26 and 38 cm BSS in both bogs (Table A1). On average, they were 3 cm higher during the cold season and 4 cm lower during the warm season. The means for the lagg forests were considerably lower, at 49 and 80 cm BSS on Linnusaare and Männikjärve Bogs, respectively. The mean for the treed Männikjärve marginal slope was 39 cm BSS. In all forested/treed ecotopes, GWLs were 4–5 cm higher than the mean during the cold season and 4–6 cm lower during the warm season.

The 50-year linear trends of the GWLs were very low for more than half of the analysed data ranges ($0.10 < r < 0.23$), except for the ridge-pool and treed ecotopes of Männikjärve Bog (r = 0.66, 0.53 and 0.42, respectively) (Figure 9). The Period II GWLs showed a comparatively large (5–7 cm) rise in Männikjärve ridge-pool ecotopes and a 0–3 cm fall in the rest of the bog dome ecotopes (Table A2). The GWL rose by 5 cm in Männikjärve lagg forest and fell by 6 cm and 2 cm in treed Männikjärve marginal slope and Linnusaare lagg forest, respectively.

In comparison with Period I, the PBPs of Period II GWLs in the ridge-pool ecotopes of both bogs showed identical shape changes within the same bog area. The Linnusaare Bog GWLs showed a rise of both max. and min. values, but all Li222 values were around 10 cm lower. The PBPs for the ridge-pool ecotopes of Männikjärve Bog were elevated by 1−2 cm (Figure A2). The ridge-hollow ecotopes across both bogs had identical plot shape changes during Period II, i.e. the PBPs had a constantly lowered plot form from max. towards min. values, with a sharp inclination down to 80 cm BSS within 0.2 to 0.0 quantiles. The PBPs of the forested/treed GWLs differed both within and between the bogs, i.e. changes were rather similar in the Linnusaare lagg forest and the treed Männikjärve marginal slope, with constantly lower GWL values down to 75−85 cm BSS. At the same time, PBP of the Männikjärve marginal forest rose from 0.2 to 1.0 quantile, and inclined down to 120 cm BSS within 0.0 to 0.1 quantiles.

The dominating frequency of the Period I GWLs on ridge-pool and ridge-hollow ecotopes of both bogs belonged to the 15−30 cm BSS interval (frequency = 59−74 %). The Li222 and Li220 GWLs were exceptions, with dominating frequency within the BSS interval 30−45 cm (frequency = 76 % and 53 %, respectively) (Figure A3). In general for these ecotopes, the entire oscillation amplitude of Period II GWLs increased towards lower values, with varying frequency changes in dominating GWL intervals. Exceptions were the Männikjärve ridge-pool ecotopes, where the frequency decreased in the lower GWL values and increased by 10 % within the upper 0−15 cm BSS interval. In both Linnusaare lagg forest and treed Männikjärve marginal slope, the dominating frequency of Period I GWLs belonged to the 30−45 cm BSS interval (frequency = 50 % and 49 %, respectively); in Männikjärve lagg forest it belonged to the 75−90 cm BSS interval (frequency = 38 %). During Period II in forested/treed ecotopes the prevailing frequency interval remained the same. At the same time the entire GWL oscillation amplitude (0−60 cm BSS) of the treed Männikjärve marginal slope shifted downward by 15 cm, while the amplitude for Männikjärve lagg forest (45−120 cm BSS) was enlarged upward by 15 cm, and that for the Linnusaare lagg forest remained the same (30−90 cm BSS) (Figure A2).

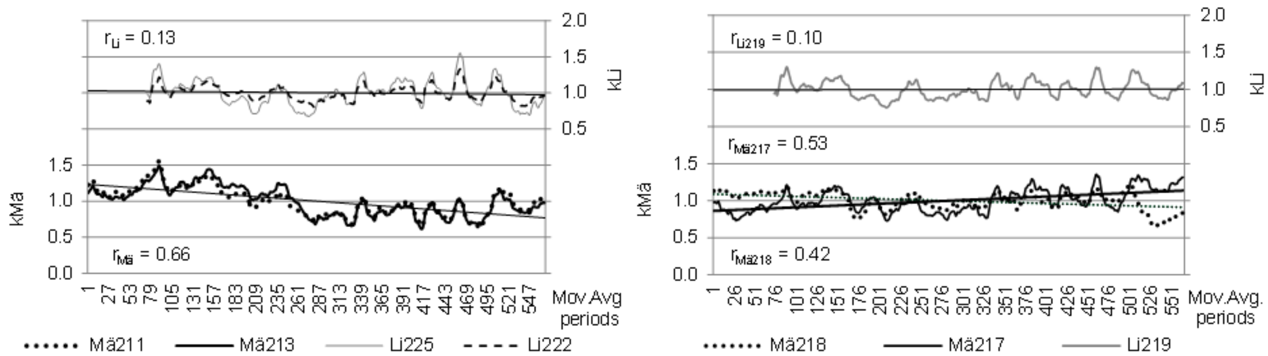

Figure 9. Linear trends of variation coefficients of groundwater levels ($k_{Mä}$, and k_{Li}, respectively) for 12-month moving average (Mov.Avg.) periods over the 50 years of observations (see Equation 1). Mä211…Li222 = ridge-pool ecotopes on the Linnusaare (Li) and Männikjärve (Mä) Bogs; Mä218…Li219 = forested/treed ecotopes.

There were three clusters in distance-scaled constellation plots of the hierarchical clustering, formed by GWLs of both bog ecotopes (Figure 10). The two largest GWL clusters of Period I were segregated by the ecotopes from the same bog area, while the Männikjärve forest ecotope stood alone (Mä218). The Period II clustering increased the consolidation of cluster pairs (increase of $r = 3$ %), whereas forested/treed ecotopes of both bogs formed a new forested/treed cluster of the pair Li219 & Mä217 and excluded the Mä218 ecotope.

Multiple relations of the average winter data

The constellation plots of average winter data (Periods I and II) show three well-distinguished Männikjärve clusters according to the type of ground-level variable that was used (Figure 11). For both periods the most stable cluster was formed by the snow data. The Period II clustering increased consolidation between cluster pairs formed by D and H microforms from the same type of ecotope. The largest cluster was formed by the GWLs of different ecotopes together with varying combinations of mean and maximum soil frost data from both D and H microforms. The Period II clustering increased the consolidation between GWLs of the same ecotope type (i.e. GWL pairs of Mä211 & Mä213 and Mä232 & Mä322 ridge-pool and ridge-hollow ecotopes, respectively) by varying combination with other cluster variables. The third cluster was formed mainly by the mean soil frost data from both D and H microforms, but with varying cluster pairs and structure over both periods.

The Period II cluster segregation is accompanied by increased regressions within the variable type used (Figure 12). During Period II the strongest regressions were found within the snow variables, followed by groundwater levels and soil frost. The Period II correlation mean (r) within the snow variable reached 0.94 (increase = 0.13; the highest $r = 0.97$ between treed D & H microforms), within groundwater levels it reached 0.78 (increase = 0.11; the highest $r = 0.93$ between Mä322 & Mä323), within mean soil frost it was 0.75 (increase = 0.23; the highest $r = 0.92$ between H microforms of treed & pool ecotopes), and within maximum soil frost it was 0.73 (increase = 0.14; the highest $r = 0.97$ between treed D & H microforms).

DISCUSSION

Changes in air temperature and precipitation

According to Estonian Weather Service (2017), the Estonian *climate normal* air temperature (T_{air}) for the period 1981–2010 is 6.0 °C and the annual precipitation is 673 mm. The length and means of the *climate normal* period fit rather well with the results for Period II (1989–2011) obtained in the present study (Table 1). Thus, the increase of central-east

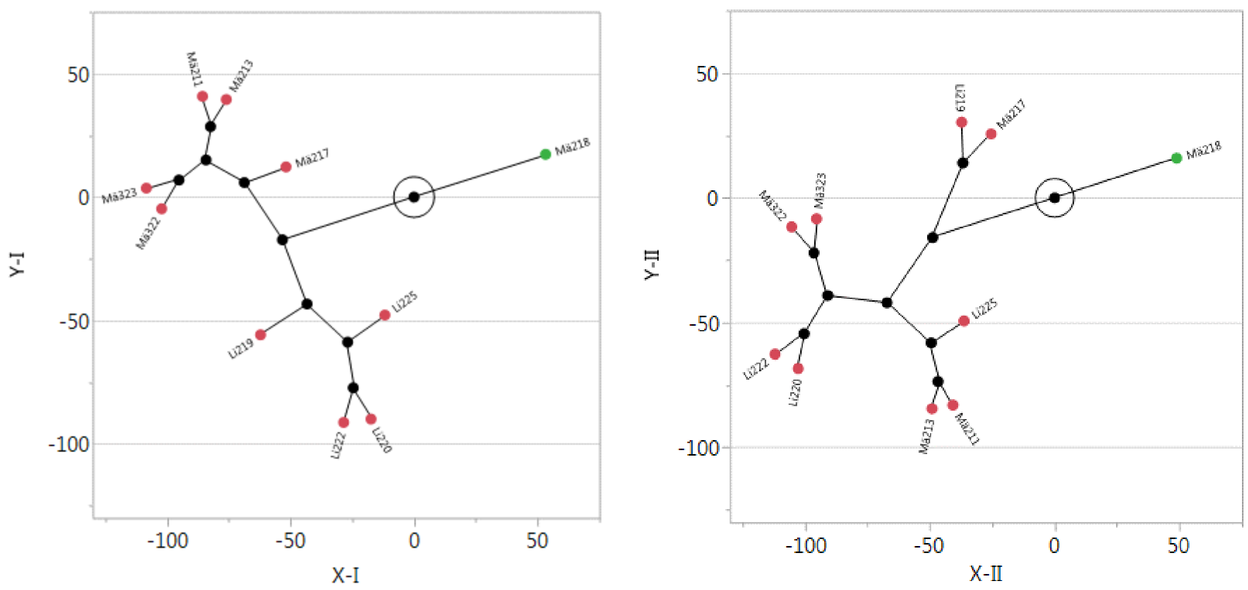

Figure 10. Constellation plots of distance-scaled dendrograms of Period I and II groundwater levels of different Linnusaare (Li) and Männikjärve (Mä) bog ecotopes. In these graphs and later: circled dot = the endpoint of hierarchically clustered data matrix (Ward method), Y and X = the endpoint co-ordinates of clustered variables. Abbreviations for variables as in Table A1).

Mires and Peat, Volume 19 (2017), Article 15, 1–21, http://www.mires-and-peat.net/, ISSN 1819-754X

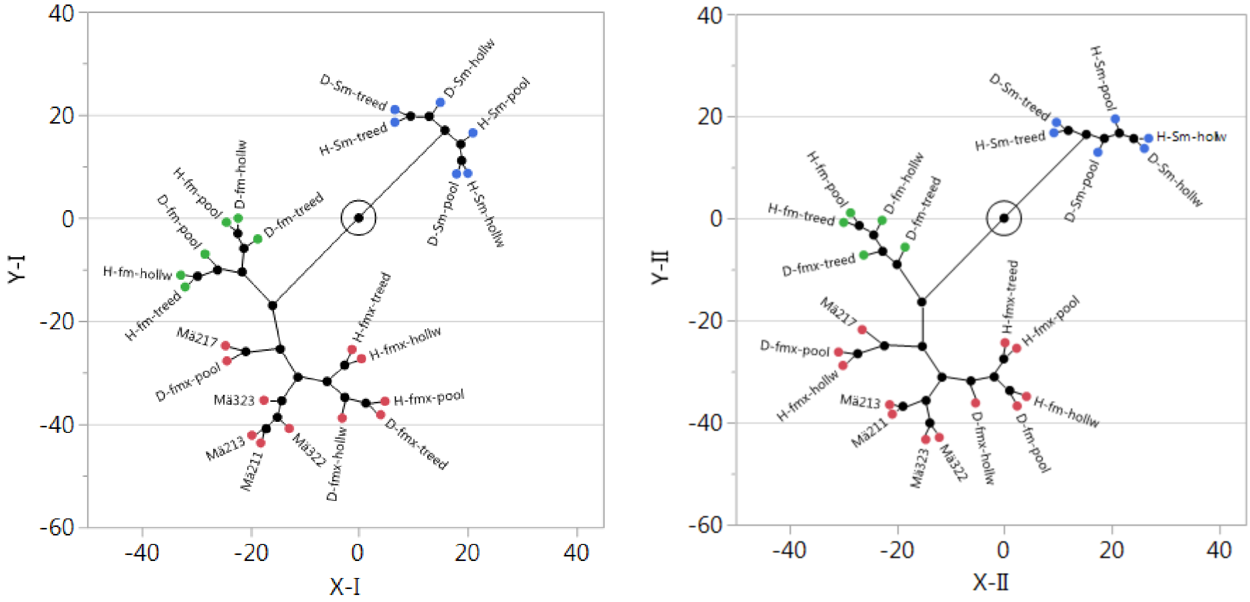

Figure 11. Constellation plots of distance-scaled dendrograms of Männikjärve Bog (Mä) ground-level variables for average winter seasons (Periods I and II). The variables used are: mean (fm) and maximum (fmx) soil frost depths; and mean snow depths (Sm) in depressions (D) and hummocks (H) of treed, ridge-hollow and ridge-pool ecotopes. Abbreviations for the ecotope groundwater levels are: Mä217 = treed; Mä322 & Mä323 = ridge-hollow; and Mä211 & Mä213 = ridge-pool. For the graph settings, see Figure 10.

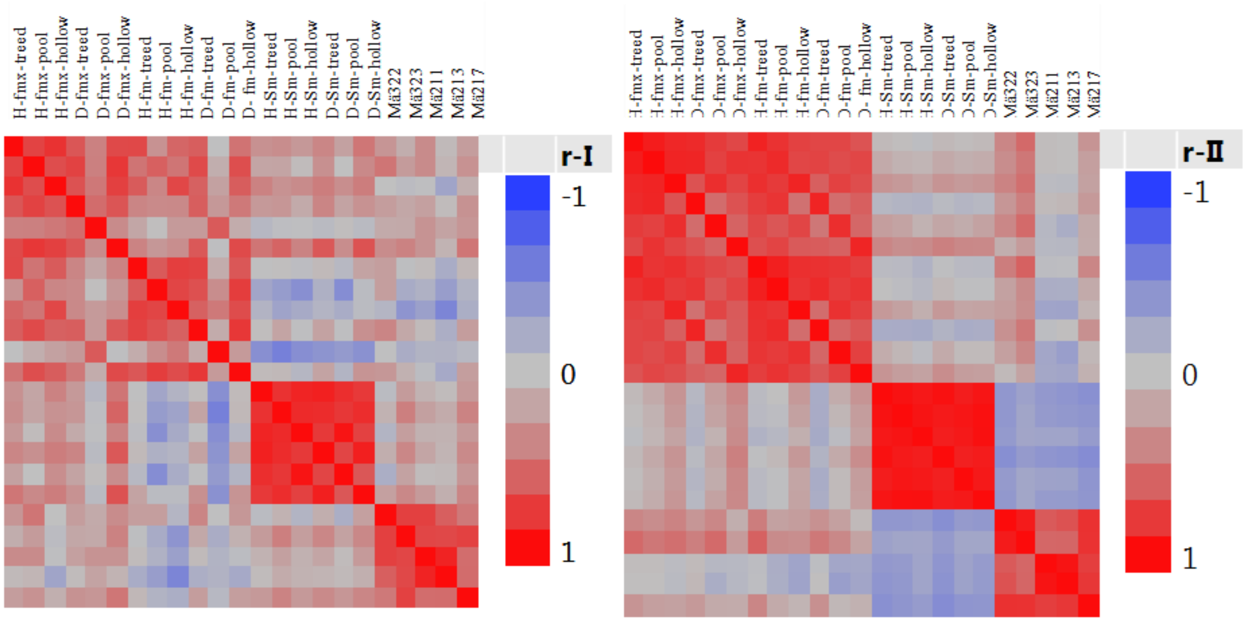

Figure 12. Multiple regressions maps (r-I, r-II) of Männikjärve Bog (Mä) ground-level variables for average winter seasons (Periods I and II). The variables used are: mean (fm) and maximum (fmx) soil frost depths; and mean snow depths (Sm) in depressions (D) and hummocks (H) of treed, ridge-hollow and ridge-pool ecotopes. Abbreviations for the ecotope groundwater levels are: Mä217 = treed, Mä322 & Mä323 = ridge-hollow, and Mä211 & Mä213 = ridge-pool ecotopes.

Estonian monthly T_{air} of 30 %, and especially the 46 % T_{air} increase of the average winter season, confirm the previous claims about winter warming in Estonia (e.g. Jaagus 2006). The increase in average winter air temperature was 1.7 °C, while warming for the coldest month was 2.4 °C.

From our results we conclude that during ecohydrologically comparable periods (1962–1988 & 1989–2011) there were almost no changes in the annual monthly precipitation amounts in our study area. The increase was ~ 2 %. However, precipitation during the cold season increased by 10 %, mainly due to a shift from smaller precipitation events towards larger (60−90 mm) ones. Precipitation during the warm season decreased by 5 % but the precipitation amplitude increased, sometimes to values of up to 240 mm *per* month.

In summary, the precipitation on the bogs increased during winter, but slightly decreased during summer.

Changes in snow cover and frost depth

Viru (2017) studied the duration of permanent snow cover in Estonia during 1951–2015 and showed that the duration of snow cover over the whole Estonia had decreased, on average, by 1–4 days for each ten years. On this basis we calculated that, in our study area, it had shortened by around 18 days. Our study also showed that the average winter soil frost (f_{mean}) on the bog decreased by 7 % , the maximum soil frost (f_{max}) decreased by 12 % and the snow depth (S) decreased by 18 %. Apart from that, the average winter warming caused a distinct increase in S and f depth variations in the bog (by 25 % and 30 %, respectively).

From our results it can be concluded that winter warming has caused a clear decrease in snow depth on the bog and has also reduced ice thickness in the bog pools. The decrease in frost depth may vary depending on the bog surface microtopography, plant cover and wetness conditions (Figure 8). In ridge-hollow ecotopes on open bog, smaller snow depth may cause slightly deeper frosts in the 'higher and drier' hummocks than in hollows; whereas in treed ecotopes (which are more sheltered), the relatively high groundwater levels during winter cause smaller frost depths in both hummocks and depressions.

Also, it should be stressed that our results do not support the "colder soils in a warmer world" hypothesis of Groffman *et al*. (2001), since the air temperature rise during Period II was associated with a slight increase in precipitation. It could be speculated that increased cyclonic activity in Estonia (Sepp *et al.* 2005) reduced the duration of frost periods between sequential precipitation events and, thus, we rather agree with the prediction of "warmer and wetter winters" due to changed climate conditions (Wu & Roulet 2014).

Changes in groundwater levels

Our analyses of monitored groundwater levels (GWLs) show that the long-term GWLs in the domes of our bogs were on average 0.3−0.4 m below soil surface (BSS), which is in good agreement with values reported from intact raised bogs in Europe (Van der Schaaf 2002). The 50-year GWLs had rather stable oscillation dynamics around their long-term averages (slightly less variation and a few cm higher during the cold season, and *vice versa* during the warm season), both on the bog dome and in the marginal lagg area. However, there were different ecotope-based GWL responses between 1989 and 2011 (Table A2). The most remarkable was a 20−30 % rise in GWL in Männikjärve ridge-pool ecotopes. This phenomenon could perhaps be explained by subsiding bog surfaces (Strack *et al*. 2008, Kont *et al.* 2007). However, the relationship between peat surface oscillation ("Mooratmung"), peat body subsidence and GWL changes expressed as absolute heights (e.g. Fritz *et al*. 2008) needs further investigation.

Our research supports the suggestion of Van der Schaaf (2002) that both mean GWL depth and the amplitude of GWL fluctuations increase from the centre of a bog towards the margins. The lower GWLs observed in our bogs are obviously related to the forested/treed ecotopes at the marginal slope and lagg areas (i.e. 0.4–0.8 m BSS). The surface slope seemed to have minor effect on GWL in the marginal treed Mä217 ecotope (a phenomenon also observed by Van der Schaaf 2002). But, in the case of Männikjärve Bog, it is probably related more to the groundwater well location (too close to the transitional zone between treed marginal slope and the bog dome; Figure 1).

The Männikjärve lagg forest seemed to represent the "classical" ecotope formed on the floodplain of the small stream, being the bog lagg at the same time. Warmer winters during the period 1989–2011 raised the cold-season forest GWL by 9 %, presumably as a result of water discharge from both the bog slope and the stream floodplain (see also Howie & Van Meerveld 2013). This is also consistent with wetter conditions on the bog during the cold season.

However, a small increase of the warm-season air temperature and a decrease in precipitation during the period 1989–2011 was reflected in a downward increment of the GWL oscillation amplitude, both on the bog domes (3−22 cm) and in the forested lagg areas (3−14 cm) (Figure A3).

As a whole, the bogs that we studied in the Endla Mire Complex still represent *centre wet* bog landscapes (Rydin *et al*. 2006) with treed margins and partly wooded ridges between pools in the centre. However, the slight long-term increase of groundwater levels at lower positions within most ecotopes over the second part of the study period is a sign of small changes towards dryer conditions. This is reflected in corresponding modifications of the plant cover (e.g. increase of tree growth) and, presumably, geophysical and biogeochemical changes in the upper layer of the peat massif at the same time (e.g. Ivanov 1981, Bragg 2002, Wu & Roulet 2014). Numerically it is reflected in increased consolidation between the groundwater data for forested/treed ecotopes over the two bogs and similarly for the bog dome ecotopes during Period II of our study (Figure 10).

Changes in multiple relations of the average winter data

Changes in multiple relations within the data for ground-level variables of the average winter season (Figures 11 and 12) show that snow depth is the most "sensitive" to winter warming, whereas changes in soil frosts depend on the bog wetness conditions created by the microtopography, plant cover and hydrophysical properties of the acrotelm or by the groundwater level dynamics. However, it seems that the use of monthly data is not fully suited to the investigation of "cause-and-effect" in winter warming conditions on the bogs due to processes related to scale differences (e.g. groundwater level and soil frost relationships) since, for example, the formation of soil frost in mires starts, as a rule, after ten days with stable air temperature below 0 ºC and the subsequent increase in frost depth continues until at least 5−10 cm of snow has accumulated (e.g. Davõdov *et al*. 1973). But how these variables react in winter seasons with more rapidly changing frost-thaw conditions, and how it is reflected in the spatial distribution of bog soil temperature, wetness conditions *etc*., needs further study.

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Appendix

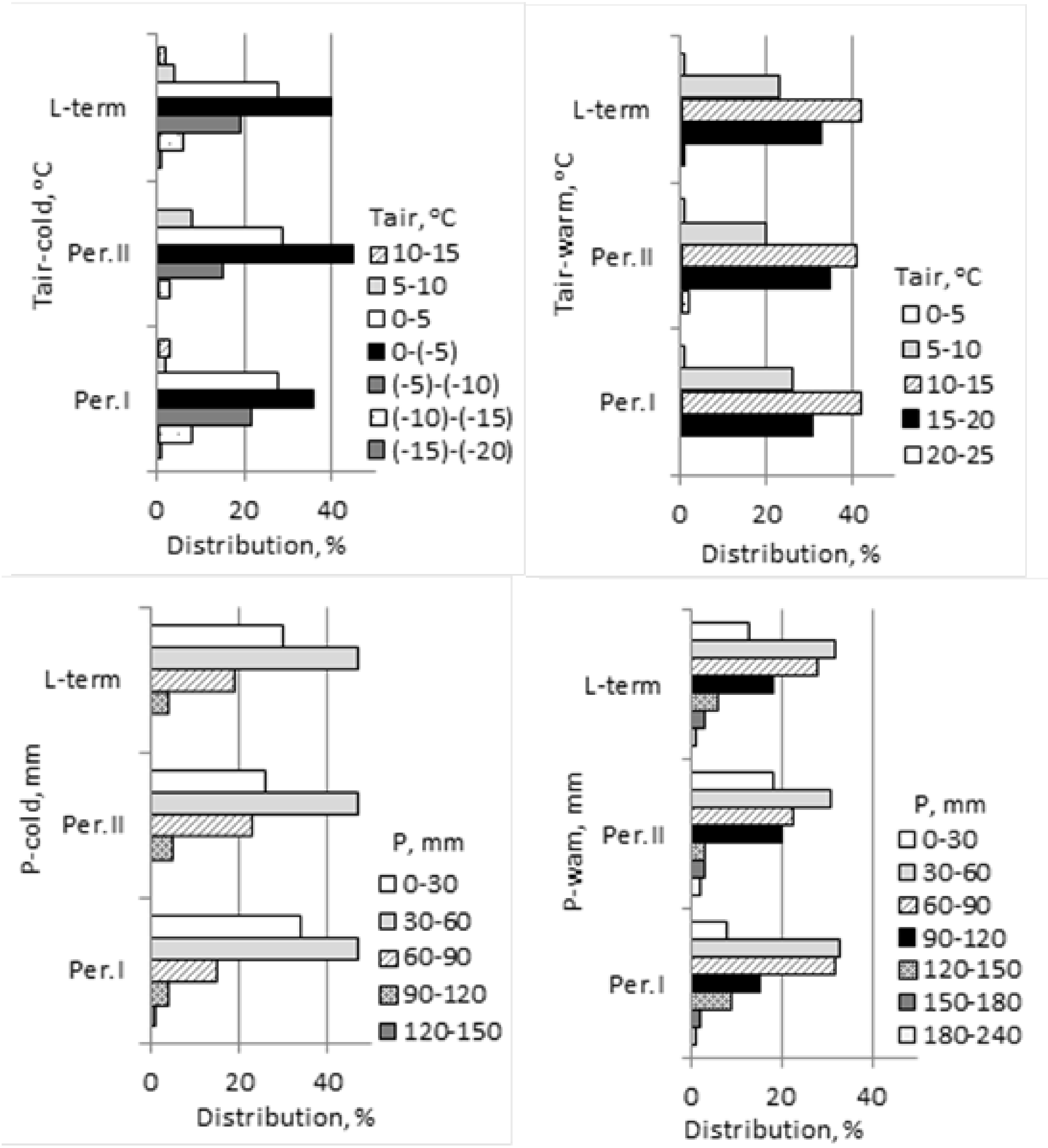

Figure A1. Frequency distribution (%) of the cold-season and warm-season T_{air} and P values during the whole 50-year study period (L-term), Period II (Per.II) and Period I (Per.I). Distribution intervals used: for T_{air} = 5 °C, for P = 30 mm.

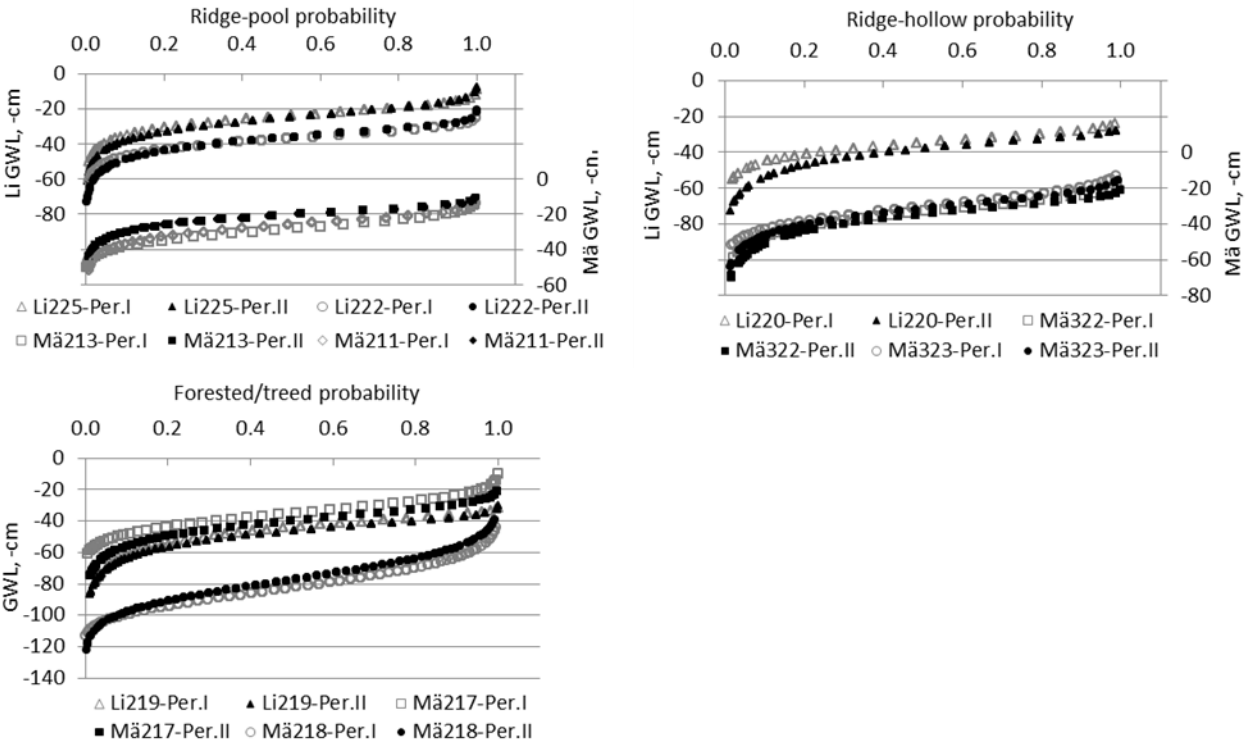

Figure A2. Probability plots of groundwater level (GWL) for Periods I and II (Per.I, Per.II) in different Linnusaare (Li) and Männikjärve (Mä) bog ecotopes.

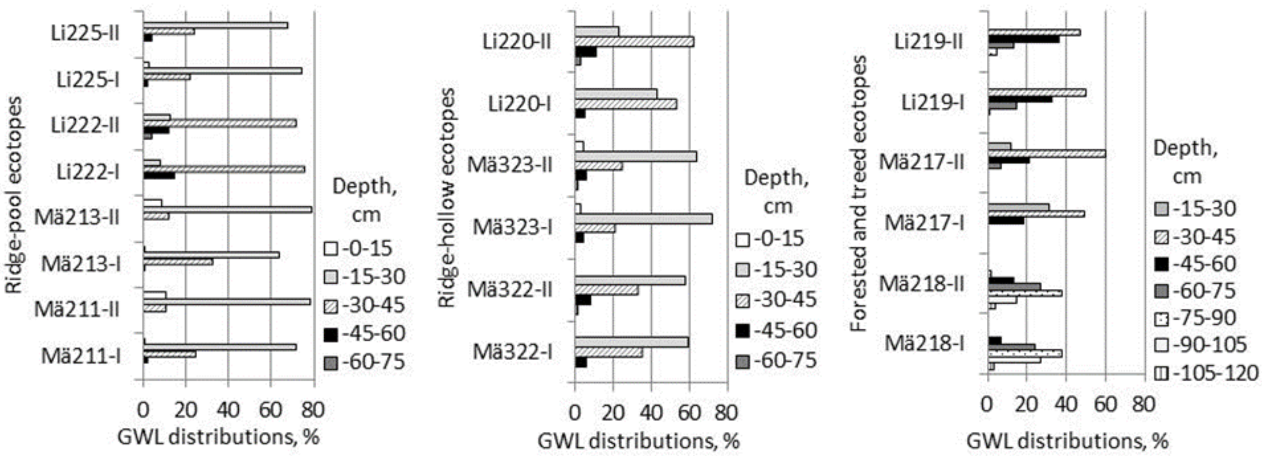

Figure A3. Frequency distribution (%) of the Period I and II groundwater levels (GWL) in different ecotopes of Linnusaare (Li) and Männikjärve (Mä) Bogs (see also Tables A1 and A2). A step of 15 cm depth is used for the GWL distribution interval.

Table A1. Statistics for 50-year monthly GWLs (cm) in different ecotopes of Linnusaare (Li) and Männikjärve (Mä) Bogs. In this Table and elsewhere, GWLs below the soil surface are indicated by "-".

		Linnusaare Bog				Männikjärve Bog					
	Ecotope	Ridge-pool		Ridge-hollow	Forested		Treed	Ridge-pool		Ridge-hollow	
	GW well	Li225	Li222	Li220	Li219	Mä218	Mä217	Mä213	Mä211	Mä323	Mä322
Annual	Mean	-26	-38	-35	-49	-80	-39	-26	-25	-27	-31
	Std.Dev.	9	8	8	11	15	11	8	7	9	9
	n	492	492	480	480	564	576	576	576	576	576
	Max	-8	-21	-14	-31	-39	-10	-11	-11	-11	-16
	Median	-25	-36	-33	-46	-80	-37	-25	-24	-25	-29
	Min	-61	-73	-73	-87	-122	-75	-50	-52	-64	-70
Cold season	Mean	-23	-35	-31	-45	-76	-34	-23	-22	-23	-27
	Std.Dev.	6	5	5	8	14	8	6	5	5	5
	n	262	262	255	255	302	309	309	309	309	309
	Max	-8	-21	-14	-31	-39	-10	-11	-11	-11	-16
	Median	-22	-34	-31	-44	-77	-34	-22	-21	-22	-27
	Min	-52	-60	-57	-80	-113	-64	-44	-42	-45	-49
Warm season	Mean	-31	-42	-39	-53	-84	-44	-30	-28	-32	-36
	Std.Dev.	9	9	9	12	15	11	8	8	10	10
	n	230	230	225	225	262	267	267	267	267	267
	Max	-12	-27	-24	-33	-44	-20	-14	-14	-13	-19
	Median	-29	-40	-37	-50	-84	-42	-29	-27	-31	-33
	Min	-61	-73	-73	-87	-122	-75	-50	-52	-64	-70

Table A2. Statistics for Period I and Period II monthly GWLs (cm) in different ecotopes of Linnusaare (Li) and Männikjärve (Mä) Bogs.

		Linnusaare Bog				Männikjärve Bog					
	Ecotope	Ridge-pool		Ridge-hollow	Forested		Treed	Ridge-pool		Ridge-hollow	
	GW well	Li225	Li222	Li220	Li219	Mä218	Mä217	Mä213	Mä211	Mä323	Mä322
Annual	I GWL mean	-26	-38	-33	-48	-82	-36	-29	-27	-26	-31
	II GWL mean	-27	-38	-36	-50	-77	-42	-22	-22	-28	-32
	±differences	-1	0	-3	-2	+5	-6	+7	+5	-2	-1
	I Std.Dev.	7	7	7	11	14	10	7	7	8	8
	II Std.Dev.	9	9	9	11	16	11	6	6	9	9
Cold season	I GWL mean	-23	-35	-30	-46	-79	-32	-26	-24	-22	-27
	II GWL mean	-22	-34	-32	-45	-72	-37	-19	-19	-24	-28
	±differences	+1	+1	-2	+1	+7	-5	+7	+5	-2	-1
	I Std.Dev.	5	5	5	9	13	8	5	5	5	5
	II Std.Dev.	6	5	6	8	15	6	3	3	6	5
Warm season	I GWL mean	-29	-42	-36	-50	-85	-40	-33	-31	-31	-35
	II GWL mean	-32	-43	-41	-55	-84	-47	-26	-25	-33	-37
	±differences	-3	-1	-5	-5	+1	-7	+7	+6	-2	-2
	I Std.Dev.	8	8	8	12	15	10	7	8	9	9
	II Std.Dev.	9	10	10	12	16	11	7	7	10	10

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