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EFFECTS OF MICROCLIMATIC AND LANDSCAPE CHANGES ON THE TEMPERATURE REGIME AND THAW DEPTH UNDER A FIELD EXPERIMENT IN THE BOLSHEZEMELSKAYA TUNDRA

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Results of a field experiment conducted in order to assess the impact of microclimatic and landscape changes on the temperature regime and thaw depth in permafrost-affected soils of subarctic ecosystems at the southern permafrost limit of the European Northeast are presented. To carry out the field experiment in 2012 in various types of tundra landscapes (vegetated surfaces of peat mounds and watershed ridges, peat circles), 15 transparent open top chambers were installed. During 2016–2018 local temperature changes above the surface (height 5 cm) and in the upper soil layer (depth 20 cm) were studied along with the change in quantitative parameters of landscape components (vegetation height, snow thickness, leaf area index, soil moisture, the depth of the suprapermafrost water-level) affecting soil temperature and the thaw depth. It was found that in the chamber contours, the winter and summer temperatures above the surface and in the upper soil layer, the vegetation height, and snow thickness statistically significantly increase, whereas an increase in the active layer thickness was insignificant. Permafrost-affected soils of peat circles and the clay loam-rich watershed ridge are found to be the most vulnerable to microclimatic and landscape changes.

Tundra, field experiment, chambers, microclimate, landscape factors, soil temperature, active layer

INTRODUCTION

Recent climate changes with their profound effect on subarctic ecosystems [*Hugelius et al., 2011; IPCC, 2014*] have resulted in a northward shift of shrub and forest vegetation [*Elsakov, Kulugina, 2014*]. Climate-induced soil temperature warming leads to permafrost melting [*Biskaborn et al., 2019*], thereby promoting greenhouse gas emissions [*Knoblauch et al., 2018*], which ultimately rebounds as amplified climate warming [*Schuur et al., 2015*]. Global climate models project a significant increase (up to 5 °C) in the mean annual air temperature (MAAT) during the 21st century which is a key indicator of Arctic climate and ecosystems status [*Koenigk et al., 2012*].

Subarctic regions of the northeast European Russia that belong to the southern permafrost zone are viewed as most sensitive to climate warming [*Oberman, Shesler, 2009*]. Recent assessments of the increasing soil temperature indicate that at the end of the 21st century, the permafrost area will significantly reduce in the region [*Stendel et al., 2011*], while permafrost in the Bolshezemelskaya tundra may survive only in the environmental conditions of peat plateaus [*Pastukhov, Kaverin, 2016; Rivkin et al., 2017*].

Presently there is a large number of research works addressing modern cryogenic soil temperature regime functioning in different permafrost landscapes [*Mazhitova, 2008; Malkova, 2010*], and forecasts of its changes for the 21st century [*Anisimov, 2009; Wisser et al., 2011*]. However, recent years have seen an increasing interest in field experiments involving monitoring of soil temperature and landscape-scale variations across permafrost ecosystems. Such studies help overcome difficulties with calibrating climate models, specifically, regional (i.e. adapted for specific landscapes) [*Hollister et al., 2006*], while field experiments enable evaluation of site-specific (local) soil-temperature and landscape responses to climate changes [*Norby et al., 1997*].

The use of electric heating cables and infrared heaters as active systems for passive warming of soils during field experiments, contribute to soil drainage and require availability of a source of permanent energy [*Shaver et al., 2000*]. Snow screens are widely used among passive warming systems for soil temperature manipulation. At this, they create artificial shading and decelerate snowmelt, which does provide additional challenges in estimating the magnitude of changes in soil temperature regime [*Natali et al., 2011*]. Open-top chambers (OTCs) used as passive soil warming systems provide for appropriate temperature warming conditions, with the heating effect being insignificant inside OTCs [*Marion et al., 1997*]. Given their optimal size, the air temperature will increase, while soil moisture changes slightly [*Henry, Molau, 1997*]. Such environmental manipulation studies have become one of major tools for conducting field passive warming experiments on responses to OTC-induced changes in microclimatic conditions during the summer season [*Voigt et al., 2017*]. The reported results of year-round experiments deploying open top chambers are acknowledged to be highly topical and have attracted great interest and attention from scientific community [*Bokhorst et al., 2013*].

The present study is a continuation of earlier research initiated by a group of scientists from the University of Eastern Finland with an aim to evaluate effects of the tundra climate warming on greenhouse gas emissions [*Voigt et al., 2017*]. Effectively, this experiment covers a larger range of landscape factors, and analyzes variations in soil (below-ground) and surface (above-ground) temperatures throughout the year, including winter season.

The purpose of this study is to assess effects of microclimatic and landscape changes (i.e. variations in snow cover depth, soil moisture, shrub stand height, leaf area index) on the temperature regime and seasonal thaw depth of permafrost-affected soils in the tundra ecosystems during manipulative warming field experiment based on the study of OTC-induced changes.

OBJECTS OF RESEARCH

The study sites are located 7 km west of Seida railway station (67°03′ N, 62°55′ E; absolute elevation 100 m a.s.l.) (Fig. 1) in the SE part of the Bolshezemelskaya tundra area (Vorkuta district of the Komi Republic) subsumed into the boreal forest-tundra subzone with massive island permafrost distribution. Peat plateaus that are widespread in the treeless watersheds, cover up to 10 % of the study area, which is a low plain having hummocky topography overlain by a thick strata of Quaternary sediments [*Mazhitova, Oberman, 2003*].

The climate is cold subarctic, moderately continental. The parameters derived from climate monitoring during the 2016–2018 hydrological years (October 1 through September 30) included: MAAT (–3.3 and –2.0 °C); sum of positive air temperatures (thawing degree days, TDD) 1717 and 1752 °C·day; sum of negative air temperatures (freezing degree days, FDD) –2913 and –2454 °C·day; mean annual precipitation 468 and 650 mm, winter precipitation 86 and 153 mm, respectively. The area is characterized by dominantly northerly winds during summer, and dominantly south-westerly and southerly during winter [*Taskaev, 1997*]. The air temperature parameters calculated specifically for the study sites were derived from the monitoring observations, while annual and winter precipitations were calculated based on the Vorkuta weather station data (67°29′ N, 64°03′ E; 183 m a.s.l.).

The study sites are located within the bounds of peat plateau (Fig. 2) and adjacent watershed ridge composed of silty-clayey deposits. The peat plateau (area: 0.6 km^2) sitting in an old lake basin with an

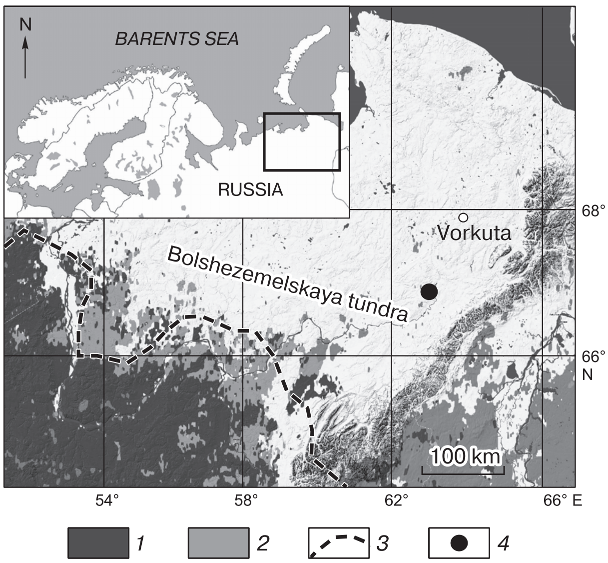

Fig. 1. Geographical position of the study sites.

1 – spruce and pine taiga forests; *2* – sparse spruce-birch forest and larch forests; *3* – southern permafrost limit; *4* – objects of research.

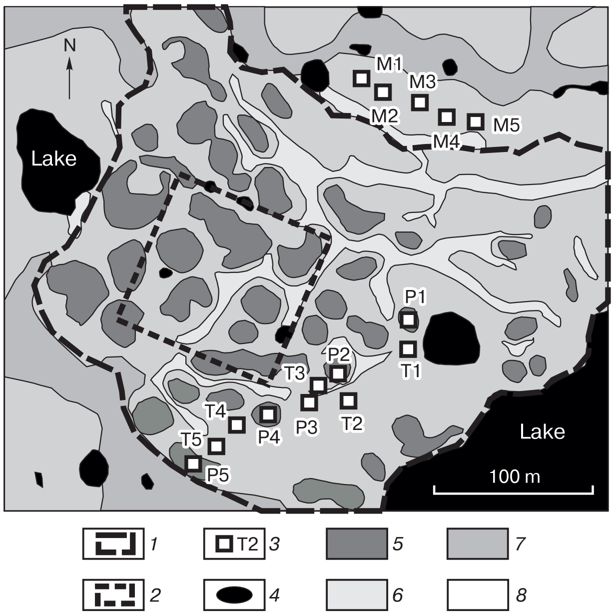

Fig. 2. Schematic map of location of the study sites.

1 – peat plateau; *2* – CALM R52 site; *3* – study sites; *4* – lakes; *5* – barren peat circles; *6* – moss-low shrub vegetation; *7* – tall-shrub vegetation; *8* – sedge-sphagnum vegetation of fens.

area of 6.7 km^2 complicated by lake terraces and thermokarst features. The peat layer reaches 4–5 m in thickness, and is underlain by Pleistocene lacustrine clay-loamy sediments [*Rivkin et al., 2017*].

The vegetation cover of the peat plateau is represented dominantly by shrub-moss-lichen communities that occupy the sloping (marginal) parts of peat mounds. Bare patches of peat (bare peat circles), almost devoid of vegetation, are developed on the peat mound tops. The watershed ridge adjoining the peat plateau abounds with shrub-moss communities. Peat oligotrophic (including degrading) permafrost-affected soils (Cryic Histosols) are widespread within the peat plateau, while permafrost-affected gleezems (Folic Cryosols) are developed on the watershed ridge [*Shishov et al., 2004; IUSS..., 2014*].

Investigations conducted by deploying regular monitoring points of the CALM R52 monitoring site have shown that the surface morphology of peat plateaus is characterized by the dominance of peat mounds (93 %), and a low fraction of fens (7 %) with permafrost table deepening down to >1 m. While peat mounds are spatially differentiated by the thickness of the seasonally thawing layer (active layer, AL): (49 ± 18) cm beneath shrub-moss communities and (53 ± 6) cm under bare peat circles [*Kaverin et al., 2019*].

RESEARCH METHODS

The experimental studies were conducted in 15 sites, of which 10 are located within peat plateau (5 sites within limits of areas dominated by shrub-moss-lichen vegetation, another 5 sites established on bare peat circles) and 5 are located on the adjacent watershed ridge (Fig. 2). Cumulatively, these sites encompass major landscape types which occupy more than 80 % of the area [*Marushchak et al., 2011*]. The index letters used for indication of the study sites are as follows: M for watershed ridge, T for peat mounds with shrub-moss vegetation, and P for bare peat circles. The site numbering is designated by numbers next to the capital index letter (M1, T4, P5, etc.). Each site is represented by two plots: control (background, or non-manipulative) plot and experimental (experimentally warmed) plot with deployed open-top chambers (OTC plot) spaced at about 3 m. The site type is marked by small letters (“k” for control plot; “e” for experimental plot) which were added to the alphanumeric index for a site: T4e, P5k, etc.

In order to provide for the experimental warming conditions capable to induce environmental changes in the landscape components, air/soil temperatures, the study sites were equipped with hexagonal OTCs in July 2012. Initially, chambers were installed soon after snowmelt and removed at the end of each field season before winter, however beginning from 2014, OTCs operate year-round. The OTCs were constructed of transparent acrylic glass which is 3 mm thick following the ITEX (International Tundra Experiment) standard [*Marion et al., 1997*]. The design of the 50 cm high chambers incorporates inward sloping (at 73°) sides and includes the chamber base (167 cm in diameter) and open space at the top (115 cm in diameter).

Regular annual measurements at each site involve estimation of the active layer thickness (third decade of September) and maximum snow cover depth (SD) (third decade of March) using a graduated metal probe. In September 2018, moisture content in the upper 10 cm soil layer and soil temperature at a depth of 20 cm were measured in all the sites. Soil temperature was determined in measurements point using a portable thermometer HANNA HI 935005 equipped with the HANNA HI 766TR2 thermocouple probe (accuracy up to 0.1 °C) with sharp tip for penetration of semi-solid soil. Soil moisture was measured using a portable HH2 Delta-T moisture measuring device (accuracy up to 0.1 %). All measurements of landscape components and AL thickness were taken three times. In 2018, relative elevations were determined for all of the study sites, with the leveling performed using the RGK T-05 digital theodolite. The landscape parameters which directly or indirectly affect thaw depth were quantified in 2018. These include: the canopy height of shrubs (cm), slopes exposure and angle (degr.), and average elevation of microrelief elements (cm). Occurrence depth of suprapermafrost vadose water was measured using plastic pipes 1.5 cm in diameter. The values of leaf surface index (LAI) were determined using a portable LAI-2200C Plant Canopy Analyzer (wave length range: 320–490 nm).

The 2016–2018 continuous monitoring of above-ground temperature was performed using HOBO U23-001 digital loggers installed at a height of 5 cm at both experimental and control plots of six sites (M1, M3, T2, T4, P3, P5). While measuring the above-ground temperature, the loggers were stowed beneath the snow cover surface most of the time during the winter season. The 2017–2018 soil temperature monitoring employed HOBO Water Pro loggers installed 20 cm below the ground at experimental and control plots of three sites (M3, T2, P3). Below-ground temperatures reported from a depth of 20 cm serve as key indicators in the in the study and classification of soil temperature regimes [*Dimo, 1972*]. Sites designated for installation of temperature loggers were chosen randomly, under condition that they are at least 50 m spaced apart. Characterization of the above-ground and top-soil temperature regimes involved calculating the mean annual temperatures by averaging all the measurements obtained, while the sum of positive (TDDs) and negative temperatures (FDDs) were obtained by adding up the mean diurnal temperatures separately for the positive and negative domains.

The two approaches applied for the statistical analysis are: (1) a pairwise comparison between temperatures obtained at experimental and control plots for each site. At this, significance of differences between the arithmetic means was evaluated using the Student's t-test, while the variance of temperature parameters was estimated from the standard deviation and Fisher's F-test; (2) comparison between the values averaged for the sites using two-factor analysis of variance (ANOVA).

The first factor is the plot type (experimentally warmed (or experimental) and control (or background)), the second factor is landscape type.

RESULTS AND DISCUSSION

Microclimate variations during the field experiment. Analysis of the control plot-based above-ground TDDs (height: 5 cm) allowed the following inferences: the control plots set up on peat circles are the coldest (Table 1); microclimate of the T4k control plot on vegetated surface of peat mound is relatively mild; thawing degree days sums (TDDs) differ slightly between the control plots; and their mean annual temperatures are dominantly negative (Table 1).

Deployment of OTCs bolster the winter microclimate mitigation, which is inferred from the increasing above-ground FDDs (Table 1). In 2016–2018, the above-ground FDDs were higher by (430 ± 167) °C·day at five of the six experimental plots as compared to the control plots. The above-ground TDDs in OTCs were higher or comparable with those measured at the control plots (Table 1). An increase in the values of this indicator for all the sites functioning in 2016–2018 was (109 ± 19) °C·day. The monthly mean temperature (July) was higher by (0.7 ± 0.2) °C in the chambers against the control plots.

Close values of temperature increase in OTCs (average: 0.95 °C, range: 0.3–2.1 °C) reported in 2012–2013 [*Voigt et al., 2017*] correlate with the data obtained for the study sites in tundra environments (North America) [*Oberbauer et al., 2007*]. At this, the observed increase in the summer air temperatures is generally consistent with the short-term climate warming scenario for the Arctic regions. Global climate models predict a 0.2–2.8 °C increase in summer temperatures by 2035 [*IPCC, 2014*]. All the experimental plots involved in the 2016–2018 manipulative warming experiment showed an increase averaging (1.3 ± 0.9) °C in the mean annual above-ground temperature, while the highest increase in the mean annual temperature is associated with the plots on bare peat circles (1.6 ± 0.8 °C).

Results of the statistical analysis showed that differences in above-ground temperatures measured in OTCs and control plots are almost always statistically significant (Table 2). This applies to both the annual indicators and those for different seasons of the year. The statistical significance of temperature differences between sites is confirmed by the p-value of the means and coefficients of variation.

Results of two-way analysis of variance (ANOVA) revealed a statistically significant effects of OTCs on the differences in the mean annual and seasonal above-ground temperatures between the experimentally warmed and control plots (Table 3). These differences were noticeable mostly in the summer and winter periods. Effects of landscape types (T, P, M), along with concerted effects of OTCs and landscape types are not statistically significant. The ANOVA analysis showed a statistically significant effect of OTC on the number of transitions of above-ground temperature (AGT) through 0 °C in the summer and autumn seasons (Table 3). The presence of OTCs

Table 1. **Key indicators of the above-ground temperature and soil temperature in control and experimentally warmed plots**

Parameter	Plot											
	M1k	M1e	M3k	M3e	T2k	T2e	T4k	T4e	P3k	P3e	P5k	P5e
2016/17	*Above-ground (height: 5 cm)*											
FDDs	–2479	–1806	–1828	–1568	–2429	–1925	–1603	–1836	–2695	–1708	–2731	–2342
TDDs	1318	1376	1360	1561	1337	1407	1282	1473	1279	1349	1328	1430
T_{annual}	–3.2	–1.2	–1.3	0.0	–3.0	–1.4	–0.9	–1.0	–3.9	–1.0	–3.8	–2.5
2017/18	*Above-ground (height: 5 cm)*											
FDDs	–2063	–1224	–1477	–1195	–1656	–1349	–1113	–1334	–1548	–1225	–2183	–1772
TDDs	1365	1356	1341	1512	1330	1372	1291	1428	1300	1352	1334	1386
T_{annual}	–1.9	0.4	–0.4	0.9	–0.9	0.1	0.5	0.3	–0.7	0.3	–2.3	–1.1
2017/18	*Soils at a depth of 20 cm*											
FDDs	–	–	–462	–317	–679	–648	–	–	–797	–606	–	–
TDDs	–	–	297	311	243	400	–	–	660	679	–	–
T_{annual}	–	–	–0.5	0.0	–1.2	–0.7	–	–	–0.4	0.2	–	–

Note. T_{annual} = mean annual temperature, °C; FDDs = sum of freezing-degree days, °C·day; TDDs = sum of thawing-degree days, °C·day. Dash = no measurements available.

Table 2. **Statistical analysis of standard deviations of the mean above-ground and soil temperatures**

Site/plot	Parameter	Year		Summer		Autumn		Winter		Spring	
		E	*S*	*E*	*S*	*E*	*S*	*E*	*S*	*E*	*S*
					2016–2018, above ground (height: 5 cm)						
M1k/M1e	*T*	–2.5/–0.4	12.5/10.3	12.4/12.7	8.4/8.6	–2.4/–1.6	8.7/8.1	–14.3/–8.2	8.5/4.3	–6.0/–4.6	6.0/3.2
	t-, *F*-criterion	17.48	1.49	1.67	1.04	4.28	1.14	42.24	3.87	13.94	3.43
	p	**0.000**	**0.000**	0.094	0.082	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**
M3k/M3e	*T*	–0.8/0.4	10.7/10.9	12.5/14.2	9.1/10.5	–1.6/–1.1	7.3/7.7	–9.5/–7.5	5.7/3.9	–4.8/–4.0	4.5/3.6
	t-, *F*-test	10.84	0.97	8.44	1.31	2.62	0.90	19.34	2.14	9.02	1.55
	p	**0.000**	0.018	**0.000**	**0.000**	**0.009**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**
T2k/T2e	*T*	–1.9/–0.7	11.8/10.7	12.4/13.0	8.5/8.9	–2.1/–1.7	8.3/7.8	–12.3/–8.4	8.1/5.0	–5.8/–5.7	4.9/4.5
	t-, *F*-test	10.50	1.22	3.09	1.10	2.60	1.13	52.59	2.63	1.45	1.15
	p	**0.000**	**0.000**	0.002	0.001	0.009	**0.000**	**0.000**	**0.000**	0.146	**0.000**
T4k/T4e	*T*	–0.2/–0.3	9.6/10.9	12.1/13.6	8.4/9.2	–1.1/–1.8	6.7/8.0	–7.1/–8.2	4.6/4.6	–4.8/–5.1	3.4/4.4
	t-, *F*-test	1.55	0.78	8.25	1.22	4.83	0.69	11.33	1.01	4.40	1.73
	p	0.120	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	0.400	**0.000**	**0.000**
P3k/P3e	*T*	–2.3/–0.3	12.0/10.0	12.0/12.6	8.0/8.3	–2.2/–1.1	9.0/7.2	–13.3/–7.5	8.9/4.3	–5.7/–5.3	4.0/3.7
	t-, *F*-test	16.63	1.45	3.26	1.09	6.36	1.57	94.08	4.37	5.26	1.18
	P	**0.000**	**0.000**	**0.001**	**0.001**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**
P5k/P5e	*T*	–3.1/–1.8	13.2/11.8	12.2/13.0	8.1/8.5	–2.1/–1.6	8.2/8.0	–15.7/–12.4	9.5/6.4	–6.9/–6.1	7.7/5.9
	t-, *F*-test	9.78	1.23	4.06	1.11	2.41	1.07	19.08	2.18	5.55	1.74
	p	**0.000**	**0.000**	**0.000**	**0.000**	0.016	**0.010**	**0.000**	**0.000**	**0.000**	**0.000**
					2017–2018, in soil (depth: 20 cm)						
M3k/M3e	*T*	–0.45/–0.02	2.77/2.23	2.21/2.45	1.78/1.75	1.03/0.83	1.35/1.32	–1.65/–0.99	1.50/0.77	–3.39/–2.37	2.01/1.03
	t-, *F*-test	6.60	1.55	2.67	1.04	2.79	1.05	10.45	3.86	12.18	3.84
	P	**0.00**	**0.00**	**0.01**	0.32	**0.01**	0.25	**0.00**	**0.00**	**0.00**	**0.00**
T2k/T2e	*T*	–1.20/–0.68	3.48/3.84	1.89/3.34	1.58/2.32	0.72/0.94	1.02/1.50	–2.01/–1.83	2.26/1.72	–5.36/–5.16	2.89/2.77
	t-, *F*-test	5.38	1.22	14.01	2.17	3.28	2.16	1.67	0.58	1.35	0.92
	p	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	0.10	**0.00**	0.18	0.12
P3k/P3e	*T*	–0.38/0.20	5.38/4.82	5.73/5.92	3.65/3.81	1.46/1.38	1.93/2.04	–3.13/–1.64	3.60/1.82	–5.58/–4.88	3.17/2.66
	t-, *F*-test	4.30	1.25	0.98	1.09	0.73	1.11	9.89	0.26	4.59	0.70
	p	**0.00**	**0.00**	0.33	0.12	0.47	0.08	**0.00**	0.00	0.00	0.00

Note. *T* is the temperature, °C; *E* is the arithmetic mean with the Student's *t*-test value; *S* is the standard deviation with the Fisher's *F*-test value; *p* is the corresponding significance level. Significant indicators at the $p < 0.01$ level are shown **in bold.**

Table 3. **Two-way analysis of variance (ANOVA) of effects induced by the deployed open top chambers (OTCs) and landscape types on above-ground temperatures (height: 5 cm)**

Factor-induced effect	*df*	Above-ground temperature				Temperature transitions through 0 °C	
		E		*S*		*n*	
		F	*p*	*F*	*p*	*F*	*p*
				Year			
Chamber (OTC)	1	**6.261**	**0.046**	2.055	0.202	2.836	0.143
Landscape	2	1.956	0.222	0.939	0.442	0.176	0.842
OTC+ landscape	2	0.511	0.624	0.751	0.512	0.288	0.759
				Summer			
Chamber (OTC)	1	**10.395**	**0.018**	2.882	0.140	**19.068**	**0.005**
Landscape	2	1.062	0.403	2.431	0.169	**9.705**	**0.013**
OTC+ landscape	2	0.148	0.866	0.144	0.869	0.031	0.970
				Autumn			
Chamber (OTC)	1	3.130	0.127	0.327	0.588	0.216	0.658
Landscape	2	0.042	0.959	0.327	0.733	**11.473**	**0.009**
OTC+ landscape	2	1.449	0.307	1.007	0.420	2.122	0.201
				Winter			
Chamber (OTC)	1	**4.976**	**0.067**	**11.209**	**0.016**	0	1
Landscape	2	1.661	0.267	1.810	0.2427	0.5	0.630
OTC + landscape	2	0.428	0.670	0.645	0.5577	1.5	0.296
				Spring			
Chamber (OTC)	1	1.166	0.322	1.166	0.322	0.601	0.468
Landscape	2	0.707	0.530	0.707	0.530	1.337	0.331
OTC+ landscape	2	0.611	0.574	0.611	0.574	0.190	0.832

Note. *E* = arithmetic mean; *S* = standard deviation; *F* = value of Fisher test; *df* = degrees of freedom (number of observations); *p* = level of significance; *n* is the number of AGT transitions through 0 °C. Significant indicators are shown **in bold**.

caused a considerable decrease in the number of AGT transitios through 0 °C in summer and autumn for all the landscape types. The exception is sites established on bare peat circles, where an increase in number of AGT transitions through 0 °C is observed in autumn (Fig. 3). Most numerous AGT transitions through 0 °C are reported in summer and autumn for all landscape types. Given that the above-ground temperatures are in the negative domain during the winter, there are no AGT transitions through 0 °C.

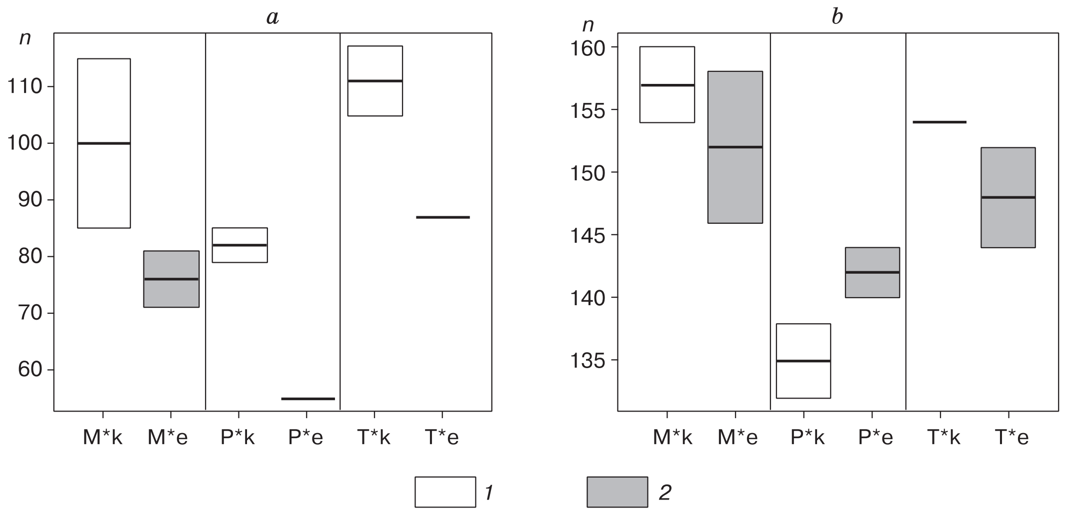

Fig. 3. Variations in number of transitions of above-ground temperatures through 0 °C (*n*) in 2016–2018 over landscape sites in summer (*a*) and autumn (*b*).

1 – control plots; *2* – experimentally warmed plots.

Landscape parameters variations during the field experiment. The local scale microclimate transformations always caused changes in the landscape components within the OTC contours. In the study period 2016–2018, the snow cover depth in the chambers was significantly (by (15 ± 1) cm) higher than it was at the control sites (Table 4). The largest increase in snow accumulation in the OTC contours (against the background plots) is associated with bare peat circles (+20 ± 2 cm) and watershed ridge (+19 ± 2 cm), and to a lesser extent – with vegetated surfaces of peat mounds (+6 ± 1 cm). Specifics of the snow accumulation differentiation within the contours of OTCs deployed at different types of sites can be explained by differentiated snow cover depth in natural environmental conditions. Bare peat circles are characterized by the lowest snow cover depth, while its greatest depth is observed in vegetated areas of peat plateau (Table 4). Alternatively, intensified snow accumulation and declined wind speed (i.e. because of shielded space) will essentially mitigate the microclimate for vegetation [*Carlsson, Callaghan, 1991; Marion et al., 1997*]. The thermal protection effect offered by snow for tundra vegetation is more important than summer warming of the air layer above soil surface [*Wahren et al., 2005*].

An increase in the height of shrub canopy within the OTC contours was (10 ± 3) cm within the peat plateau and (14 ± 3) cm on the watershed ridge. The interplay between the increased height and closeness of shrub canopy prime for even greater snow accumulation, thereby intensifying thermal protection of the vegetation cover [*Myers-Smith, Hik, 2013*]. In recent decades, the greatest expansion of tundra shrub vegetation has been observed particularly on clay-loamy soils against the backdrop of climate warming and increasing winter precipitation in the region [*Elsakov, Kulugina,* 2014].

Shrubs which grow taller in the OTC contours are characterized by an increase in the leaf area (LAI) index for the watershed ridge (+0.8 ± 0.2), while such changes on peat mounds are significantly differentiated and not statistically significant (0 ± 0.5). Similar changes were recorded in 2013, when even a decreasing trend in LAI values was observed in the vegetation cover of peat mound [*Voigt et al., 2017*].

The maximum increase in the LAI was established for drier experimentally warmed plots M2e and M5e of the watershed ridge (Table 4). An increase in the height of shrub canopy and LAI at individual sites of the watershed ridge can be explained by initially lower density of shrub canopy and more favorable growing conditions offered by clay-loamy soils which are characterized by higher thermal conductivity during summer compared to peat [*Ershov, 1988*].

Moisture content in the top soil layer in the OTC contours was lower by (3 ± 1) % in comparison with the control plots in the second half of the 2018

Table 4. **Mean values and standard deviations of the landscape components and soil temperature parameters on the experimentally warmed (experimental plots) and control (non-manipulative) plots of the study sites**

Parameter	Data	Plot								Effects of experimental warming	
		experimental	control	Te	Tk	Pe	Pk	Me	Mk	F	p
Monitoring observations data, 2015–2018											
Maximal snow depth, cm	2016	45 ± 12	30 ± 17	55 ± 9	49 ± 11	34 ± 10	19 ± 12	45 ± 4	12 ± 6	17.59	$\mathbf{3.22 \cdot 10^{-4}}$
	2017	46 ± 10	28 ± 16	55 ± 11	46 ± 10	38 ± 7	11 ± 8	45 ± 2	27 ± 8	39.052	$\mathbf{1.85 \cdot 10^{-6}}$
	2018	50 ± 12	36 ± 19	61 ± 14	57 ± 13	40 ± 4	21 ± 12	48 ± 5	31 ± 10	13.38	$\mathbf{1.25 \cdot 10^{-3}}$
Active layer thickness, cm	2015	67 ± 32	66 ± 29	45 ± 7	45 ± 7	50 ± 8	49 ± 5	106 ± 24	103 ± 20	0.017	0.897
	2016	73 ± 29	76 ± 38	52 ± 3	51 ± 7	56 ± 7	53 ± 5	110 ± 16	126 ± 24	0.674	0.420
	2017	69 ± 36	68 ± 40	43 ± 4	40 ± 4	50 ± 3	48 ± 2	115 ± 24	116 ± 34	0.046	0.833
	2018	70 ± 36	68 ± 38	44 ± 3	41 ± 2	51 ± 5	49 ± 4	115 ± 25	113 ± 34	0.148	0.704
Single observations data, 2018											
Height of plants, cm	22.09.18	27 ± 21	19 ± 14	39 ± 9	29 ± 5	0 ± 1	0 ± 1	43 ± 8	29 ± 2	15.43	$\mathbf{6.31 \cdot 10^{-4}}$
Leaf area index (LAI)	07.08.18	–	–	2.8 ± 1.7	2.7 ± 0.6	–	–	1.8 ± 0.5	1.0 ± 0.2	1.119	0.30588
Soil moisture (depth: 0–10 cm), %	15.08.18	22 ± 9	25 ± 8	18 ± 5	25 ± 7	31 ± 8	33 ± 6	18 ± 7	18 ± 5	0.97	0.33455
	22.09.18	31 ± 10	37 ± 10	24 ± 9	31 ± 7	38 ± 4	46 ± 7	33 ± 12	33 ± 9	2.535	0.12442
Soil water depth, cm	18.08.18	–	–	–	–	–	–	39 ± 13	46 ± 9	–	–
Soil temperature (depth: 20 cm), °C	22.09.18	4.1 ± 1.1	3.7 ± 1.1	3.0 ± 0.9	2.7 ± 0.7	5.0 ± 0.3	4.6 ± 0.4	4.1 ± 1.0	3.8 ± 1.3	1.249	0.27475
Thaw depth, cm	04.08.18	55 ± 24	51 ± 21	36 ± 2	33 ± 2	45 ± 5	44 ± 4	85 ± 15	76 ± 14	–	–

Note. Mean value of the parameter for sites 1–5 in each landscape type (M = watershed ridge; T = peat mounds with shrub-moss vegetation; P = bare peat circles). Plots: k = control, e = experimental. Significant statistical coefficients are shown **in bold** ($p < 0.01$). Dash = not determined.

growing season. A decrease in soil moisture was also observed on the vegetated surfaces of peat mounds (–5 ± 2 %) and in bare peat circles (–4 ± 2 %), while moisture content in soils of the watershed ridge practically did not differ from the control plots (Table 4). A slight decrease in soil moisture is probably because of lower summer precipitation captured in the contours of passive greenhouse apparatus with partially open tops. Effects of winter precipitation are neglected in this case, since measurements of soil moisture were not taken after snowmelt.

The depth of the suprapermafrost vadose water occurrence in clay-loamy soils changed differentially (–7 ± 8 cm) beneath OTCs (Table 4). The suprapermafrost vadose water level has risen at three and fell at two study sites within the watershed ridge (M1, M5). The suprapermafrost vadose water level lowering largely implies a decrease in moisture content in clay-loamy soils within OTCs, however its differentiation may be complicated by the impact of other landscape factors.

Soil temperature variations during the field experiment. Results of the monitoring studies report the minimum FDDs (sum of negative temperatures) in the control plot soil on barren peat circle P3k (Table 1). Clay-loamy soil at the control plot M3k was found to be the warmest under the background (non-manipulative) winter climatic conditions. According to the sums of TDDs, the peat-circle soil is the warmest among the background plots, while the peat-mound soil beneath the shrub-moss vegetation is the coldest. A similar tendency is observed for the values of the mean annual soil temperatures at the control plots (Table 1). Warmer temperatures of the peat-circle soil versus the clay-loamy soil temperature profile can be explained by early snowmelt (end of April – beginning of May) and low albedo of the exposed barren peat surface. In addition, soil profile at the M3 site is characterized by a relatively thick (13 cm) organogenic horizon.

Changes in the microclimate and landscape components are shown to exert influence on belowground temperatures during the field experiment. Soils in OTCs are warmer in winter compared to soils at the control (non-manipulative) plots. An increase in FDDs by (27 ± 20) °C·day is expressed more pronouncedly within watershed ridge and bare peat circle (Table 1). A noticeably greater snow accumulation (i.e. snow depth) occurred under the experimental conditions is interpreted as a major factor (contribution: 10–30 %) causing an increase in winter soil temperatures [*Lawrence, Slater, 2010; Salmon et al., 2016*].

The sum of positive soil temperatures is significantly higher (by (15 ± 20) °C·day) than those for the control plots (Table 1). During the experiment, the sum of positive soil temperatures within bare peat circle and watershed ridge does not increase that much as compared to the temperature profile of vegetated surface of peat plateau (Table 1). This result is to some extent comparable with data from point temperature measurements (Table 2). An increase in air and soil temperatures in OTCs during summer is largely prompted by mitigated wind speed (in shielded space) and enhanced capture of infrared radiation reflected from the surface [*Carlyle et al., 2011*].

Table 5. **Periods of near-zero temperatures in soils at a depth of 20 cm**

Plot	Autumn season			Spring season		
	Beginning	End	Duration, days	Beginning	End	Duration, days
M3k	22.10.17	23.11.17	32	19.05.18	20.06.18	32
M3e	22.10.17	22.11.17	31	20.05.18	13.06.18	24
T2k	17.10.17	23.11.17	37	21.05.18	16.06.18	26
T2e	16.10.17	09.11.17	24	21.05.18	14.06.18	24
P2k	17.10.17	25.11.17	39	30.05.18	07.06.18	8
P3e	18.10.17	15.11.17	28	31.05.18	10.06.18	10

The maximum average soil temperature (8–9 °C) in July was recorded at the control and experimental plots set up on bare peat circle. Under the experimental conditions, the highest increase in the mean July temperature (+2.2 °C) relative to the control plot was observed in the peat mound soil (T3e). The results obtained at these sites earlier were practically identical [*Voigt et al., 2017*].

While the mean annual soil temperature at the experimental plot (–0.2 ± 0.4 °C) was higher than at the control plots (–0.7 ± 0.4 °C), positive mean annual temperature was recorded in soils of the experimental plot set up on bare peat circle (Table 1). An increase in the soil temperature is generally comparable with the values of above-ground temperatures warming under the experimental conditions [*Salmon et al., 2016*]. In the context of non-continuous distribution of high-temperature permafrost (0...–2 °C), even a slight (0.5 °C) increase in average annual ground temperature will prime the permafrost extent for considerable reduction in the region [*Oberman, Shesler, 2009*].

The soil temperatures measured in OTCs and at the control plots differed generally essentially, the greatest differences in soil temperatures were notably expressed in spring and winter (Table 2). Compared to the control plots, the coefficients of variation in OTCs decreased both for soil temperature and aboveground temperature (Table 2). At this, temperature fluctuations were depressed to the most in winter, which is associated with enhanced snow accumulation in the OTC contours. Among the landscape types, the values of the coefficient of temperature variation decreased to a greater extent for the sites set up on bare peat circles.

The temperature data analysis showed that deployment of OTCs reduces the period of near-zero temperatures (zero curtain) in the top soil layer (Table 5). This period tends to increase most significantly in autumn in the soils of both sites (T2, P3) in the peat plateau. During the autumn period, soils of bare peat circles, as well as at other study sites, are characterized by essentially long period of near-zero temperatures. However, in spring, such a period tends to significantly reduce in these soils, primarily because of rapid thawing of upper peat horizons in the bare circles with a low albedo.

Variation in active layer thickness during the field experiment. Cumulative changes in the microclimate and landscape components that induce changes in the soil temperature regime do affect the seasonal thaw depth [*Salmon et al., 2016*]. The average active layer thickness (ALT) at the end of the growing season for all the sites in 2015–2018 was only (1.5 ± 1) cm higher in OTCs than at the control plots (Table 4). While the ALT gain in the OTC contours was not statistically significant. Nevertheless, the implications of the deployed OTCs gradually increased for ALT over the years of AL monitoring. The maximum differences in this indicator (5 ± 1 cm) were observed in 2018 (Table 4). During first years of the experiment (2012–2013), ALT changed fairly negligibly [*Voigt et al., 2017*].

The rate of thaw progression is largely governed by gradual "accumulation of heat" in soils whose effect begins to manifest itself fully only in 5–6 years time following the installation of OTCs [*Salmon et al., 2016*]. In 2018, the greatest difference between the experimental and control plots in thaw depth was observed for plots set up on the ridge, specifically, in clay-loams (7 ± 1 cm). The permafrost-affected clayey soils functioning in the region in the context of recent climate warming are known to thaw faster than peaty soils [*Oberman, Shesler, 2009*].

CONCLUSION

Deployment of transparent open-top chambers (OTCs) during the manipulative warming field experiment proved to be effective for inducing changes in local climatic, landscape, and soil-geocryological conditions in the southern limit of the European NE of Russia.

Under the experimental conditions, there is a tendency for increase in above-ground mean annual temperatures, in sum of positive temperatures (TDD) in summer, and in particular, in sum of negative temperatures (FDD) in winter. At the experimental plots, the number of transitions of above-ground through 0 °C decreases during the summer and autumn periods. At this, the autumn period of zero curtains reduces in the upper layer of permafrost-affected soils. An increase in snow accumulation during the experiment amounts to higher thermal protection (from cold winter air) of the tundra shrub vegetation. Accordingly, the height of shrub canopy increases within vegetated patches in the tundra.

Thus, during the manipulative warming field experiment, mitigation of microclimatic conditions was observed against the backdrop of increasing snow accumulation and affiliated growth of tundra shrub vegetation which therefore have caused a remarkable warming of temperature in the upper horizons and a slight increase in thaw depth, or active layer thickness. In this context, in the southern permafrost zone of the region, the projected climate and landscape changes will favor a material increase in soil temperatures promoted by abounding clay-loamy soils and peat plateaus covered by barren peat circles.

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References

Anisimov, O.A., 2009. Stochastic modelling of the active layer thickness under conditions of the current and future climate. Kriosfera Zemli (Earth's Cryosphere), XIII (3), 36–44.

Biskaborn, B.K., Smith, S.L., Noetzli, J., et al., 2019. Permafrost is warming at a global scale. Nature Communications 10 (264), 1–11, DOI: 10.1038/s41467-018-08240-4.

Bokhorst, S., Huiskes, A., Aerts, R., et al., 2013. Variable temperature effects of Open Top Chambers at polar and alpine sites explained by irradiance and snow depth. Global Change Biology 19, 64–74, DOI: 10.1111/gcb.12028.

Carlsson, B.A., Callaghan, T.V., 1991. Positive plant interactions in tundra vegetation and the importance of shelter. J. Ecology, No. 79, 973–983.

Carlyle, C.N., Fraser, L.H., Turkington, R., 2011. Tracking soil temperature and moisture in a multi-factor climate experiment in temperate grassland: do climate manipulation methods produce their intended effects. Ecosystems, No. 14, 489–502. – https://doi.org/10.1007/s10021-011-9425-y

Dimo, V.N., 1972. Thermal regime of soils in the USSR. Kolos, Moscow, 360 pp. (in Russian).

Elsakov, V.V., Kulugina, E.E., 2014. Vegetative cover of Yugra Peninsula in the context of rapid climate change over the past decades. Issledovaniya Zemli iz Kosmosa (Study of Earth from Space), No. 3, 65–77 (in Russian).

Ershov, E.D. (Ed.), 1988. Geocryology of the USSR. European Area of the USSR. Nedra, Moscow, 358 pp. (in Russian).

Henry, G., Molau, U., 1997. Tundra plants and climate change: the International Tundra Experiment (ITEX). Global Change Biology, No. 3, 1–9.

Hollister, R.D., Webber, P.J., Nelson, F.E., et al., 2006. Soil thaw and temperature response to air warming varies by plant community: results from an open-top chamber experiment in northern Alaska. Arctic, Antarctic and Alpine Res. 38, 206–215.

Hugelius, G., Virtanen, T., Kaverin, D., et al., 2011. High-resolution mapping of ecosystem carbon storage and potential effects of permafrost thaw in periglacial terrain, European Russian Arctic. J. Geophys. Res.: Biogeosciences 116 (G3), 1–14, DOI: 10.1029/2010JG001606.

IPCC: Climate Change 2014: Synthesis Report, 2014. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Core Writing Team / R.K. Pachauri, L.A. Meyer (Eds.)), IPCC, Geneva, Switzerland, 151 pp.

IUSS Working Group WRB, 2014. World Reference Base for Soil Resources 2014. International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Rep., No. 106. FAO, Rome, 191 pp.

Kaverin, D.A., Pastukhov, A.V., Novakovsky, A.B., et al., 2019. Landscape and climatic factors impacting the thaw depth in soils of permafrost peat plateaus (on the example of CALM R52 site). Earth's Cryosphere XXIII (2), 53–60.

Knoblauch, C., Beer, C., Liebner, S., et al., 2018. Methane production as key to the greenhouse gas budget of thawing permafrost. Nature Climate Change 8, 309–312, DOI: https://doi.org/10.1038/s41558-018-0095-z.

Koenigk, T., Brodeau, L., Graversen, R., et al., 2012. Arctic climate change in 21st century CMIP5 simulations with EC-Earth. Climate Dynamics 40 (11–12), 2719–2743, DOI: 10.1007/s00382-012-1505-y.

Lawrence, D.M., Slater, A.G., 2010. The contribution of snow condition trends to future ground climate. Climate Dynamics 34 (7–8), 969–981. – https://doi.org/10.1007/s00382-009-0537-4

Marion, G., Henry, G., Freckman, D., et al., 1997. Open-top designs for manipulating field temperature in high-latitude ecosystems. Global Change Biology, No. 3, 20–32.

Marushchak, M.E., Pitkamaki, A., Koponen, H., et al., 2011. Hot spots for nitrous oxide emissions found in different types of permafrost peatlands. Global Change Biology 17, 2601–2614, DOI: 10.1111/j.1365-2486.2011.02442.x.

Malkova, G.V., 2010. Mean annual ground temperature monitoring at the Bolvansky geocryological station. Kriosfera Zemli (Earth's Cryosphere), XV (3), 3–14.

Mazhitova, G.G., 2008. Soil temperature regimes in the discontinuous permafrost zone in the northeast European Russia. Eurasian Soil Science, No. 1, 48–62.

Mazhitova, G., Oberman, N., 2003. Permafrost mapping of Northeast European Russia based on the period of climatic warming 1970–1995. Norwegian J. Geography 57 (2), 111–120, DOI: doi.org/10.1080/00291950310001513.

Myers-Smith, I.H., Hik, D.S., 2013. Shrub canopies influence soil temperatures but not nutrient dynamics: An experimental test of tundra snow-shrub interactions. Ecology and Evolution, No. 3 (11), 3683–3700, DOI: 10.1002/ece3.710.

Natali, S.M., Schuur, E.A.G., Trucco, C., et al., 2011. Effects of experimental warming of air, soil and permafrost on carbon balance in Alaskan tundra. Global Change Biology 17 (3), 1394–1407.

Norby, R.J., Edwards, N.T., Riggs, J.S., et al., 1997. Temperature-controlled open-top chambers for global change research. Global Change Biology, No. 3, 259–267.

Oberbauer, S.F., Tweedie, C.E., Welker, J.M., et al., 2007. Tundra CO_2 fluxes in response to experimental warming across latitudinal and moisture gradients. Ecological Monographs 77, 221–238, DOI: 10.1890/06-0649.

Oberman, N.G., Shesler, I.G., 2009. Modern and forecasted changes in cryological conditions in the northeast European Russian Federation. In: Problems of the North and the Arctic of the Russian Federation. Scientific-inform. Bullet., No. 9, 96–106. – http://council.gov.ru/files/journalsf/number/20090922141450.pdf

Pastukhov, A.V., Kaverin, D.A., 2016. Ecological state of peat plateaus in northeastern European Russia. Rus. J. Ecology 47 (2), 125–132.

Rivkin, F.M., Vlasova, Yu.V., Parmuzin, I.S., 2017. Study of changes in permafrost conditions caused by frozen ground thaw subsidence. Earth's Cryosphere XXI (6), 21–30.

Salmon ,V.G., Soucy, P., Mauritz, M., et al., 2016. Nitrogen availability increases in a tundra ecosystem during five years of experimental permafrost thaw. Global Change Biology 22 (5), 1927–1941, DOI: 10.1111/gcb.13204.

Schuur, E.A.G., McGuire, A.D., Schaedel, C., et al., 2015. Climate change and the permafrost carbon feedback. Nature 520, 171–179.

Shaver, G., Canadell, J., Chapin, F., et al., 2000. Global warming and terrestrial ecosystems: a conceptual framework for analysis. Bioscience, No. 50, 871–882.

Shishov, L.L., Tonkonogov, V.D., Lebedeva, L.L., Gerasimova, M.I. (Eds.), 2004. Russian Soils Classification and Diagnostic. Oykumena, Smolensk, 342 pp. (in Russian).

Stendel, M., Christensen, J.H., Marchenko, S., et al., 2011. Size matters – very high resolution permafrost simulations on the 4 km scale in northeast European Russia. Geophys. Res. Abstracts, No. 13, EGU2011-6493, 6493.

Taskaev, A.I. (Ed.), 1997. Climate and Hydrology Atlas of the Komi Republic. Drofa i Dik, Moscow, 115 pp. (in Russian).

Voigt, C., Marushchak, M.E., Lamprecht, R.E., et al., 2017. Increased nitrous oxide emissions from Arctic peatlands after permafrost thaw. In: Proc. of the National Academy of Sciences of the USA, vol. 114 (24), pp. 6238–6243. – https://doi.org/10.1073/pnas.1702902114

Wahren, C.H.A., Walker, M.D., Bret-Harte, M.S., 2005. Vegetation responses in Alaskan arctic tundra after 8 years of a summer warming and a winter snow manipulation experiment. Global Change Biology 11, 537–552, DOI: 10.1111/j.1365-2486.2005.00927.x.

Wisser, D., Marchenko, S., Talbot, J., et al., 2011. Soil temperature response to 21st century global warming: the role of and some implications for peat carbon in thawing permafrost soils in North America. Earth System Dynamics Discussions, No. 2 (1), 121–138. – https://doi.org/10.5194/esd-2-121-2011

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