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Inconsistent response of Arctic permafrost peatland carbon accumulation to warm climate phases

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Key Points:

- Carbon accumulation in Arctic permafrost peatlands responds inconsistently to warm climate phases
- Recent warming is reflected as increase but also decrease in carbon accumulation
- Permafrost peatlands are creating a negative feedback to climate warming, but have a probable future scenario to turn to a positive feedback

Abstract

Northern peatlands have accumulated large carbon (C) stocks since the last deglaciation and during past millennia they have acted as important atmospheric C sinks. However, it is still poorly understood how northern peatlands in general and Arctic permafrost peatlands in particular will respond to future climate change. In this study, we present C accumulation reconstructions derived from 14 peat cores from four permafrost peatlands in northeast European Russia and Finnish Lapland. The main focus is on warm climate phases. We used regression analyses to test the importance of different environmental variables such as summer temperature, hydrology and vegetation as drivers for non-autogenic C accumulation. We used modeling approaches to simulate potential decomposition patterns. The data show that our study sites have been persistent mid- to late-Holocene C sinks with an average accumulation rate of 10–80

32.40 g C m^{-2} y^{-1}. The warmer climate phase during the Holocene Thermal Maximum stimulated faster apparent C accumulation rates (ACARs) while the Medieval Climate Anomaly did not. Moreover, during the Little Ice Age, ACARs were controlled more by other factors than by cold climate per se. Although we could not identify any significant environmental factor that drove C accumulation, our data show that recent warming has increased C accumulation in some permafrost peatland sites. However, the synchronous slight decrease of C accumulation in other sites may be an alternative response of these peatlands to warming in the future. This would lead to a decrease in the C sequestration ability of permafrost peatlands overall.

1 Introduction

Previous peatland studies have suggested that during warm climate phases, e.g., the Holocene Thermal Maximum (HTM, ~ 9000-5000 years ago; Yu et al., 2009) and the Medieval Climate Anomaly (MCA, ~ 950 to 1200 AD; Charman et al., 2013), northern peatland carbon (C) accumulation rates were higher than during cool climate phases. These data originated mainly from boreal peatlands, but comparable data are still scarce at higher latitudes (but see Sannel et al., 2017; Swindles et al., 2015). Thus, the response of Arctic peatlands to, for instance, recent warming (Hartmann et al., 2013) remains uncertain despite the fact that future warming may result in major changes in C accumulation in these high-latitude peatlands. This is partly because warming increases the growing season length and therefore plant productivity, while at the same time plant physiology and decay rates of plant litter are affected by changes in soil moisture conditions. Moisture is an important factor that controls plant net primary productivity (NPP) through impacting photosynthesis (Field et al., 1995). The estimated rate of permafrost loss may be c. 4.0 million km^2 per one degree warming (Chadburn et al., 2017) and permafrost landscapes are likely to get wetter (Oberman, 2008; Romanovsky et al., 2010) or drier (Zhang et al., 2018) in the future depending on microtopographical features. Interlinked changes in temperature and moisture conditions may trigger shifts in vegetation composition (e.g., Zhang et al., 2018) and consequently cause significant changes in C accumulation patterns (Charman et al., 2013; Treat et al., 2016). Moreover, permafrost thaw may expose substantial quantities of old stored organic C to decomposition (Jones et al., 2017; O'Donnell et al., 2012). This could potentially be released to the atmosphere as carbon dioxide (CO_2) and/or methane (CH_4), leading to a positive climate feedback (Hodgkins et al., 2014). The two possible divergent responses of Arctic peatlands i) an increase in carbon accumulation due to increases in photosynthetic input or ii) an increase in decomposition of plant litter and old carbon due to drying and/or warming, are challenges for C cycle models and future projections (e.g., Schuur et al., 2009). Will predicted changes in permafrost peatland dynamics lead to a positive or a negative feedback to global warming?

In order to address this question, we selected four permafrost peatlands in northeast European Russia and Finnish Lapland. These regions have experienced increasing temperatures in recent decades (Bekryaev et al., 2010; Bulygina & Razuvaev, 2012; Mikkonen et al., 2015). We investigated changes in C accumulation rates over the past few millennia using a total of 14 peat cores. There was a special focus on warming phases, aiming to provide information for understanding C accumulation responses to future climate warming. Additional local proxy data coming from testate amoeba and plant macrofossil analyses, supplemented by available regional scale tree ring-based summer temperature reconstructions (Wilson et al., 2016) allowed us to evaluate correlations between C accumulation patterns and various environmental variables.

2 Study sites

The study sites are permafrost peatlands in the discontinuous permafrost zone of Russia and the sporadic permafrost zone in Finnish Lapland (Fig. 1 and Table 1). Indico and Seida are located in the Arctic northeast European Russian tundra, where extensive permafrost aggradation occurred from ca. 2200 cal. BP onwards (Hugelius, et al., 2012; Routh et al., 2014). During the MCA, permafrost thawing and subsequent desiccation was recorded in our study sites (Zhang et al., 2018). In some parts of our sites, post-Little Ice Age (LIA) warming since 1850 AD has caused permafrost thawing and triggered *Sphagnum* establishment while a stronger recent warming has started to desiccate the peat surface (Zhang et al., 2018). The peat plateaus both at Seida and Indico are elevated a few meters from the surrounding mineral soil, and the vegetation is dominated by shrub-lichen-moss communities, such as *Betula nana*, *Rhododendron tomentosum*, *Empetrum nigrum*, *Polytrichum strictum*, *Sphagnum fuscum*, *S. lindbergii* and sedges of *Eriophorum* spp. In contrast to Seida, peat plateau vegetation at Indico is dominated by lichens and mosses, with less abundant shrubs. On both peat plateaus there are areas of bare peat 0.4 meters across (Repo et al., 2009; Ronkainen et al., 2015).

In the Finnish Lapland sites Kevo and Kilpisjärvi, permafrost probably initiated during the LIA around 500-100 cal. BP (Oksanen, 2006; Zhang et al., 2018). Vegetation at both sites is dominated by dwarf shrubs, e.g. *Betula nana*, *Empetrum nigrum*, *Rubus chamaemorus*, *Polytrichum strictum*, *Dicranum* spp, and *Sphagnum* mosses such as *S. fuscum*, *S. balticum*, *S. majus* and *S. riparium* along a hydrological gradient. The sedge *Eriophorum vaginatum* is also present. At Kevo and Kilpisjärvi, there are also patches of bare peat, but they are smaller and less extensive than those present in the Russian sites.

Fig. 1. Location of the study sites (red dots). Climate data for each site are derived from the nearest meteorological station (blue stars), see details in Table 1. Data for circum-Arctic permafrost zonation map are edited from Brown et al. (1998).

3 Materials and methods

3.1 Sampling

In total, 14 active layer peat cores (Table 1) were collected from four sites in August 2012 (Russia) and 2015 (Finland) using a 5 cm diameter Russian peat corer. Individual cores were wrapped in plastic and returned to the lab in sealed PVC tubes and stored in a freezer. The cores were later defrosted and subsampled at 1-cm or 2-cm contiguous slices and stored in plastic bags for further analyses.

3.2 Chronology

Due to a lack of preserved and identifiable plant macrofossil remains in our cores, 44 bulk peat samples were sent to the Finnish Museum of Natural History (LUOMUS, Helsinki, Finland) and the Poznan Radiocarbon Laboratory (Poznan, Poland) for accelerator mass spectrometry (AMS) ^{14}C dating (Table 1 and S1). The chronology of the top part of five cores (Table 1) was determined using ^{210}Pb dating. A dry 0.2-0.5 g homogenized subsample from each 1-cm interval was analyzed for ^{210}Pb activity after spiking with a ^{209}Po yield tracer. Details of the applied ^{210}Pb dating method can be found in Ali et al. (2008) and a modified version from the University of

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Supporting Information for

Inconsistent response of Arctic permafrost peatland carbon accumulation to warm climate phases

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Introduction

This supporting information provides the age-depth models of studied 14 peat cores (Fig. S1) and non-autogenic carbon accumulation patterns for 14 peat cores (Fig. S2). Table S1 shows radiocarbon dating and peat property details. Table S2-S3 show the derived parameters and results from the used modeling approaches. Table S4 shows the results of multiple linear regression analysis of apparent carbon accumulation and environmental variables.

Fig. S1. Age-depth models of studied peat cores from four permafrost peatlands. Post-bomb dates are shown in green and pre-bomb dates are shown in blue.

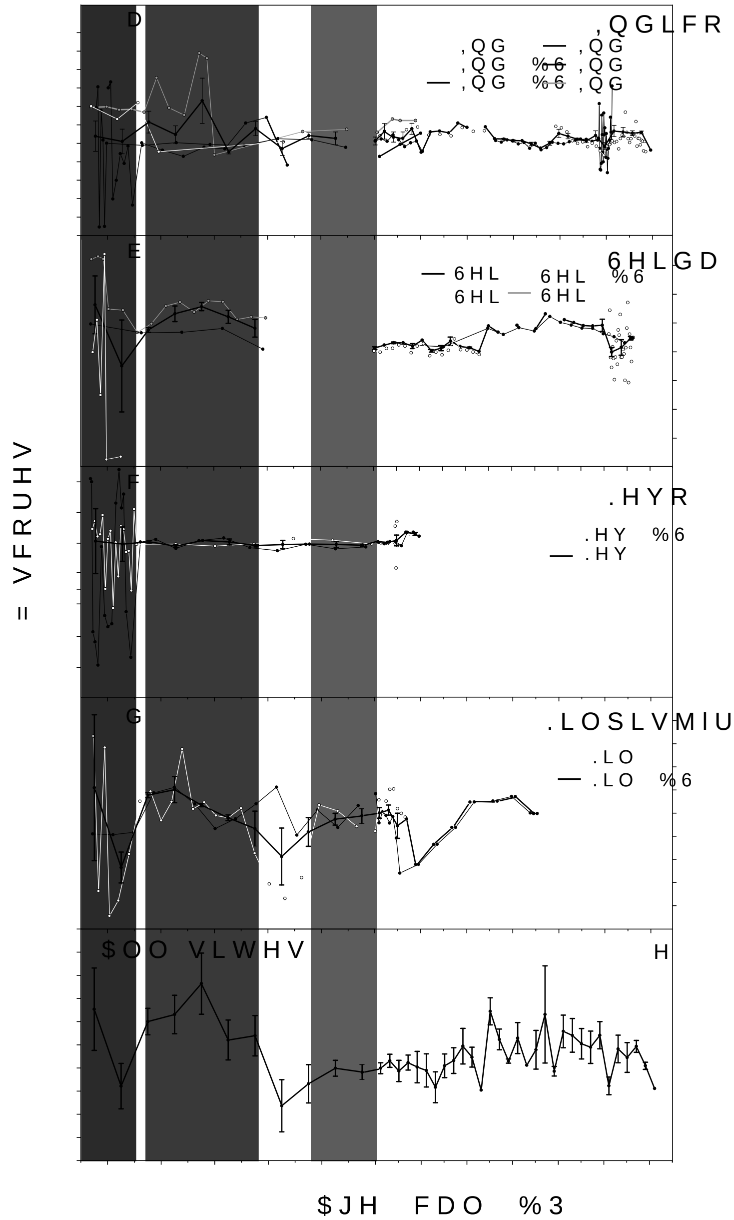

Fig. S2. (a-d) Non-autogenic carbon accumulation z scores for four permafrost peatlands with error bars representing standard errors of the means. Up to 1000 yr BP, calculations are for each 100-yr bin, for later periods, calculations are for each 200-yr bin. (e) Combined data for all sites are shown. Samples that may be influenced by uncertainty of ^{14}C dating were removed (see text for details). Climate phases are indicated using purple (Medieval Climate Anomaly), grey (Little Ice Age) and red (recent warming) shadings.

Core	Dated depth (cm)	Age (BP)	cal. BP	PAR range	BD (g cm^{-3})	LOI (%)	C (%)	N (%)	C/N ratio
Ind1	6-8	220 – 30	235	0.04-1.00	0.11 – 0.02	78.14 – 7.67	-	-	-
	12-14	1686 – 40	1615						
	24-26	1785 – 30	1700						
	38-40	3216 – 36	3420						
Ind2 BS	0-1	4385 – 35	4950	0.08-0.43	0.08 – 0.02	-	49.95 – 1.59	0.83 – 0.18	62.42 – 11.05
	8-9	5240 – 35	6035						
	19-20	5708 – 30	6490						
	37-38	6109 – 31	7040						
Ind3 BS	1-2	3425 – 35	3660	0.08-0.88	0.07 – 0.03	-	50.68 – 1.33	0.41 – 0.18	148.61 – 65.44
	19-20	5182 – 28	5950						
	47-48	5466 – 31	6260						
Ind4	19-20	109 – 22	125	0.07-2.00	0.09 – 0.04	-	48.22 – 3.24	1.25 – 0.43	35.25 – 8.11
	34-35	2066 – 25	2050						
Ind5	25-26	726 – 24	675	0.02-1.23	0.10 – 0.06	-	44.92 – 4.18	1.00 – 0.51	36.26 – 6.91
	34-35	4105 – 35	4700						
	44-45	6308 – 33	7230						
Ind6	12-14	240 – 30	230	0.06-0.70	0.07 – 0.02	79.22 – 5.54	-	-	-
	24-26	345 – 35	400						
	42-44	1941 – 35	1885						
Sei1	8-10	560 – 30	580	0.02-0.13	0.17 – 0.08	71.04 – 18.9	-	-	-
	14-16	3230 – 35	3495						
	22-24	4245 – 40	4780						
	38-39	5775 – 38	6575						
Sei2	6-7	1105 – 30	1010	0.01-1.43	0.20 – 0.05	-	50.26 – 1.62	2.26 – 0.61	24.48 – 8.78
	7-8	1050 – 30	* 965						
	23-24	3085 – 30	3295						
Sei3 BS	0-1	5220 – 40	5970	0.48	0.07 – 0.01	-	51.79 – 0.80	2.27 – 0.22	23.17 – 2.27
	25-26	5690 – 40	6485						
Sei4	6-8	100.51 – 0.34 (pMC)	-5	0.04-0.1	0.07 – 0.01	93.71 – 5.70	-	-	-
	28-30	580 – 37	580						
Kev1 BS	0-1	105.92 – 0.34 (pMC)	-57	0.07-1.03	0.11 – 0.03	-	52.67 – 0.79	1.69 – 0.11	31.23 – 2.08
	17-18	50 – 30	140						
	26-27	1540 – 30	1445						
	30-31	1610 – 30	1485						
Kev2	18-19	380 – 30	410	0.08-2.53	0.14 – 0.04	-	51.62 – 2.07	1.83 – 0.38	29.35 – 5.83
	32-33	2020 – 30	1975						
Kil 1 BS	0-1	106.57 – 0.34 (pMC)	-56	0.02-0.13	0.15 – 0.02	-	51.84 – 2.40	2.05 – 0.15	25.27 – 2.00
	21-22	1650 – 30	1570						
	28-29	3965 – 35	4450						
	30-31	4065 – 35	4540						
	39-40	3575 – 30	* 3900						
Kil 2	17-18	600 – 30	585	0.12-0.57	0.13 – 0.02	-	47.68 – 6.17	1.77 – 0.26	27.86 – 6.46
	20-21	495 – 30	* 525						
	31-32	1750 – 30	1645						
All cores					0.13 – 0.06	79.67 – 13.86	50.23 – 4.37	1.49 – 0.70	51.94 – 50.71

PAR: peat accumulation rate (mm yr^{-1}); BD: bulk density; LOI: loss on ignition. The values of BD, LOI, C and N content (%) are present as mean – standard deviation. pMC: percentage modern carbon. *Ages are removed from age-depth modeling.

Table S1. Radiocarbon dating details and peat properties of peat cores in this study.

	Dec$_{part}$ peat			Dec$_{full}$ peat				Dec$_{part}$ peat			Dec$_{full}$ peat		
	p	!	adj.R^2	p	!	adj.R^2		p	!	adj.R^2	p	!	adj.R^2
Ind1	19.44–4.78	35.65	0.9847	40.10–1.15	2.00	0.9883	Sei4	34.07–0	49.98	0.9999	12.60–0.18	3.00	0.9926
				4.46–0.50	0.24	0.9879	Kev1 BS	87.30–1.43	8.70	0.9999	10.00–0.24	2.75	0.9853
Ind4	187.90–14.27	117.70	0.9934	12.90–0.12	2.48	0.9997					79.30–2.58	5.40	0.9885
Ind5	68.29–2.66	50.29	0.9982	17.94–1.32	9.57	0.9829	Kev2	154.70–8.36	53.58	0.9910	15.50–0.25	0.18	0.9992
Ind6	12.50–0.21	4.11	0.9917	4.32–0.58	1.09	0.9825	Kil1 BS	22.3–0.75	12.1	0.9909	28.40–1.04	8.43	0.9841
Sei1	2.79–0	5.55	0.9999	5.19–0	0.29	0.8828					22.20–0.63	2.46	0.9999
Sei2!	98.97–9.84!	114.80!	0.9846!	17.37–0.14!	0.24!	0.9997!	Kil2 !	62.69–4.21!	63.46!	0.9954	29.60–0.46!	4.18!	0.9984

Values in italic represent the sections that may be impacted by uncertainty of dating and removed from further analysis

Table S2. Results of the exponential decay modeling of all studied peat cores, with partially decomposed (Dec$_{part}$) and fully decomposed (Dec$_{full}$) peat sections processed separately. p: peat addition rate (g m^{-2} yr^{-1}), ! : peat decay coefficient (*10^{-4} yr^{-1}).

	Remaining C mass (g m^{-2} yr^{-1})			NCU (g m^{-2} yr^{-1})		Remaining C mass (g m^{-2} yr^{-1})			NCU (g m^{-2} yr^{-1})
	initial input	after 100 yrs	after 300 yrs			initial input	after 100 yrs	after 300 yrs	
Ind1	9.72	8.82	4.70	4.04	Sei4	17.35	11.36	6.82	12.6
Ind4	93.95	43.16	20.73	6.56	Kev1 BS	43.65	40.16	34.61	5.63
Ind5	34.15	22.72	13.61	9.21	Kev2	77.35	50.36	29.67	8.00
Ind6	6.25	6.00	5.56	7.11	Kil1 BS	11.15	9.95	8.18	7.83
Sei1	1.40	1.32	1.20	4.94	Kil2	31.35	19.18	10.79	13.77
Sei2	49.49	23.04	11.14	8.70					

Table S3. Comparisons between the expected remaining C mass of present peat after 100, 300 years decomposition and the net peat C uptake (NCU) of past few millennia.

	! -Coefficients (SE)	Standardized !	95% CI	p-value
Intercept	57.24 (18.74)	-	19.82 to 94.66	0.003
T_{sum}	22.53 (6.94)	0.32	8.68 to 36.39	0.002
WTD	6.28 (2.59)	0.24	1.11 to 11.46	0.018
UOM	-0.40 (0.16)	-0.26	-0.72 to -0.07	0.017
N%	-13.99 (8.51)	-0.24	-30.97 to 2.99	0.11
C/N ratio	-0.16 (0.23)	-0.09	-0.62 to 0.30	0.50
Herbaceous	-0.01 (0.14)	-0.01	-0.29 to 0.28	0.97
Ligneous	0.09 (0.09)	0.11	-0.09 to 0.27	0.30

T_{sum}: summer temperature; WTD: water-table depth; UOM: unidentifiable organic matter; N%: nitrogen content; C/N: carbon/nitrogen; CI: confidence interval.
* adj. R^2 = 0.42, $p < 0.001$.

Table S4. Multiple linear regression modeling* of relationship between apparent carbon accumulation rates and environmental variables for all sites combined dataset.