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Short Communication
Influence of permafrost on water storage in West Siberian peatlands revealed from a new database of soil properties

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ABSTRACT

Russia's West Siberian Lowland (WSL) contains the most extensive peatlands on Earth with many underlain by permafrost. We present a new database of 12 705 measurements of vertical water content and bulk soil properties from 98 permafrost and non-permafrost cores collected in raised bogs and peat plateaus across the region, together with *in-situ* measurements of surface moisture and thaw depth, botanical descriptions of dominant surface vegetation species assemblage, and field notes. Data analyses reveal significant contrasts ($p < 0.01$ to $p < 0.0001$) between permafrost and non-permafrost sites. On average, permafrost WSL peatlands exhibit drier surfaces, shallower depth, lower organic matter content and higher bulk density than do non-permafrost sites. Peat bulk density and ash-free density increase with depth for non-permafrost but not for permafrost sites. Gravimetric water content averages 92.0% near the surface and 89.3% at depth in non-permafrost, but 81.6% and 85.4%, respectively, in permafrost, suggesting that the disappearance of permafrost could produce moister surfaces across the WSL. GIS extrapolation of these results suggests that WSL peatlands may contain ~1200 km^3 of water and ice, a large storage equivalent to ~2-m average liquid water depth and approximately three times the total annual flow in the Ob' River. A global estimate of ~6900-km^3 subsurface water storage for all northern peatlands suggests a volume comparable to or greater than the total water storage in northern lakes. The database is freely available as supplementary material for scientific use at http://onlinelibrary.wiley.com/doi/10.1002/ppp.735/suppinfo. Copyright © 2012 John Wiley & Sons, Ltd.

Supporting information can be found in the online version of this article.

KEY WORDS: peatland; permafrost; water; soil moisture; bulk density; Braun-Blanquet system; vegetation; *Sphagnum*; West Siberian Lowland; soils database

INTRODUCTION

Russia's West Siberian Lowland (WSL) contains nearly 600 000 km^2 of peatlands with depths greater than 0.5 m, the most extensive such deposits on Earth (Sheng *et al.*, 2004). Since the early Holocene, these peatlands have behaved as a globally significant CH_4 source and a long-term sink for atmospheric CO_2 (Smith *et al.*, 2004; MacDonald *et al.*, 2006). However, like other northern peatlands, the region's short- and near-term behaviour as a net source or sink for atmospheric carbon remains a subject of ongoing discussion and debate (e.g. Baird *et al.*, 2009; Dorrepaal *et al.*, 2009; McGuire *et al.*, 2009; Schuur *et al.*, 2009; Rennermalm *et al.*, 2010; Kim *et al.*, 2011).

Of prime interest is whether the historical role of peatlands as long-term carbon sinks - as well as their role as home to a unique biodiversity and as hydrological buffers and reservoirs - might change in the future in response to

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changing climate (e.g. Ise *et al.*, 2008; Baird *et al.*, 2009; Rennermalm *et al.*, 2010). Ensemble projections of general circulation models predict warmer temperatures, longer growing seasons and enhanced precipitation, with high confidence around the northern high latitudes (ACIA, 2005; IPCC AR4, 2007). In response, net primary productivity and litter production are expected to increase, but so also will soil microbial activity, enhancing the loss of sequestered carbon through the release of CH_4 and/or CO_2 to the atmosphere (Dorrepaal *et al.*, 2009; Schuur *et al.*, 2009). Projecting the likely net result of these opposing ecosystem processes on peatland carbon sink/source status requires further research and modelling, and, given the substantial differences in climate (Yu *et al.*, 2009) and permafrost status (Turetsky *et al.*, 2002) between peatland provinces, the response of the carbon balance will likely be region-specific. New models (e.g. Weiss *et al.*, 2006; Bohn *et al.*, 2007; Wania *et al.*, 2009) and observational datasets are needed to provide insights on peatland surface moisture and water content, because aerobic dry peats emit a greater fraction of CO_2 whereas anaerobic wet peats predominately release CH_4. As such, hydrology is a crucial factor governing the exchange of greenhouse gases between peatlands and the atmosphere (Charman, 2002; Johansson *et al.*, 2006; Petrescu *et al.*, 2008).

A key influence on the hydrology of northern peatlands is the presence or absence of permafrost (Christensen *et al.*, 2004; Jorgenson and Osterkamp, 2005; Quinton *et al.*, 2009). Circumpolar mapping northwards of 45°N suggests that on average the presence of permafrost roughly doubles the prevalence of ponded surface water, with a circumpolar average of ~11.8 large lakes per 1000 km^2 in permafrost peatlands, but only 6.1 lakes per 1000 km^2 in non-permafrost peatlands (Smith *et al.*, 2007). Remote sensing has been used to detect lake reductions over time, which in turn may reflect changing permafrost conditions (Yoshikawa and Hinzman, 2003; Smith *et al.*, 2005; Riordan *et al.*, 2006; Kirpotin *et al.*, 2009; Lu and Zhuang, 2011). For example, lake expansion and thermokarst processes may be observed on the land surface, especially in ice-rich permafrost (Sollid and Sørbel, 1998; Zuidhoff and Kolstrup, 2000; Payette *et al.*, 2004; Sannel and Brown, 2010). However, datasets of *in-situ* vertical peat soil properties and water content - especially ones spanning both permafrost and non-permafrost locations across large areas - are rare.

We present in this paper a new database of peat soil bulk properties and water contents from West Siberia, together with *in-situ* observations of thaw depths, live surface botany and moisture content, stratigraphic notes, geographic coordinates, GPR information and other field data for nearly 100 peatlands distributed across the WSL. A GIS-based extrapolation of these measured moisture characteristics to the nearly 10 000 peatlands previously mapped for the region (Sheng *et al.*, 2004) provides a first estimate of total subsurface water storage in WSL peatlands. The new database (see Supplementary material) is freely available for scientific use at http://onlinelibrary.wiley.com/doi/10.1002/ppp.735/suppinfo.

STUDY REGION

The WSL extends over ~2.6 × 10^6 km^2 and 24 degrees of latitude (~50-74°N), spanning a substantial climatic gradient with mean annual air temperatures ranging from -10°C to +2°C (Frey and Smith, 2005). Roughly half of the WSL, mostly northwards of ~60°N, falls into zones of continuous, discontinuous, sporadic and isolated patches of permafrost. Topographic relief is limited (~0-250 m a.s.l) with abundant standing water and a low-gradient drainage pattern dominated by the Ob'-Irtysh, Pur and Taz river systems. A low drainage divide occurs along the Sibirskie Uvaly Hills, a broad upland crossing the region from roughly east to west at ~63°N latitude.

Some 9691 peatlands with mean depths greater than 0.5 m have been mapped into a GIS database for the region, totalling 592 440 km^2 in area and storing at least 70.2 Gt of organic carbon (Sheng *et al.*, 2004). The contemporary surface of these peatlands is generally dominated by oligotrophic-raised *Sphagnum* bogs (*S. fuscum* and *S. angustifolium*) and peat plateaus, with *Hypnum* mosses and *Carex* mainly in topographic lows. Wetland structure is patchy with eutrophic fens also present. Only in the WSL's southern taiga forest belt are flat eutrophic and mesotrophic bogs found, with *Carex-Hypnum*, *Carex*, *Carex-Sphagnum*, *Phragmites* and forest bogs also occurring alongside *Sphagnum* (Kremenetski *et al.*, 2003).

In the late 1990s, a special initiative of the US National Science Foundation Arctic System Science Program called RAISE (Russian-American Initiative on Shelf-Land Environments of the Arctic) sponsored several major field-based research collaborations between US and Russian scientists working in Siberia. As part of RAISE, three intensive drilling and river-sampling campaigns were conducted throughout the WSL, during the months of July and August in 1999, 2000 and 2001 (Smith *et al.*, 2000). The study ultimately yielded 98 peat cores and other field observations spread across nearly ~1000 km and 15 degrees of latitude (~53–68°N) of the WSL. The original design of these campaigns was to core understudied peatlands between ~60° and 68°N latitude and ~70° to 80°E longitude, but several southern sites were also targeted. An unusual feature of the WSL is that owing to extensive coverage by peatlands and fens, dryland vegetation is relatively limited. Thus, the sampling design captured a gradual transition from non-permafrost peatlands in the south, in the taiga-peatland belt, across forest-tundra and eventually to open tundra in the north. In the forest-tundra zone, sampling sites frequently encountered discontinuous permafrost associated mainly with peat plateaus.

The outcome of this project was a series of publications and datasets on WSL peatland evolution (Smith *et al.*, 2000, 2004; Kremenetski *et al.*, 2003; MacDonald *et al.*, 2006; Beilman *et al.*, 2009; Velichko *et al.*, 2011), land cover (Sheng *et al.*, 2002, 2004; Frey and Smith, 2007) and river geochemistry (Frey and Smith, 2005; Frey *et al.*, 2007a, 2007b; Frey and McClelland, 2009). In addition, thousands of laboratory measurements of bulk soil properties were extracted from the 98 cores, and numerous samples of surface moisture and live plant botany were collected. The compilation, dissemination and first analysis of this unique dataset are the subject of this paper.

DATA AND METHODS

For site selection, preference was given to *Sphagnum*-dominated raised bogs and peat plateaus. Margins and swales were avoided, and GPR was used to examine peat thickness variability for sites cored in 1998 and 1999. Owing mainly to the region's pervasively-flat underlying topography, a general uniformity in peat thickness was found (Sheng *et al*., 2002). Cores in permafrost terrain were extracted using a 7-cm motorised CRREL permafrost drill. Thaw depths at these sites were measured with a ruled tape from the live vegetation surface to the topmost frozen soil horizon. Because these measurements were made in July and August they underestimate the depth of the active layer. In non-permafrost peatlands, cores were extracted using a 5-cm rotating sleeve side-cut Russian corer.

Both coring methods allowed complete sampling of peats through to the underlying sediments, generally comprising sand, silt or loam with some occurrence of gyttjas. Where observable, the nature of this underlying geological material was recorded. Owing to the large volumes of peat material collected, nearly all cores were subsampled in the field at 10-cm spacing using a saw (frozen peat) or knife (unfrozen peat) and the subsample transferred to individual airtight plastic Whirl-Pak sample bags for transport. Ten cores, ranging from 99 to 400 cm in depth, were removed in their entirety. At 76 core sites, ~200-g grab samples of live bryophytes (usually *Sphagnum*) were manually extracted from representative hummock and hollow locations and sealed in airtight plastic Whirl-Pak sample bags for later determination of gravimetric surface moisture content. A standard botanical description of dominant surface vegetation species assemblage was conducted near each borehole, using the Braun-Blanquet system. In cases when plant species identification was difficult, specimens were preserved in a herbarium for identification at a later date. Geographic coordinates of all sites were estimated using handheld GPS and recorded in field notebooks.

Laboratory processing of core and surface samples was performed in the Department of Geography at the University of California, Los Angeles following standard procedures for organic soils (Nelson and Sommers, 1996). To determine gravimetric water content, peat subsamples of known volume (1–10 mL) were extracted and weighed to obtain wet mass, then oven-dried to constant mass at 105 °C. For estimation of organic matter content, the dried samples were subjected to loss-on-ignition analysis (LOI) by heating to 550°C for 4 h and reweighing. Gravimetric water content (%) was computed in two ways: as the difference between wet mass and dry mass divided by wet mass (W_f), and as the difference between wet mass and dry mass divided by dry mass (W_d) (note that W_f and W_d are non-linearly related, i.e. $W_d = 1/(1 - W_f) - 1$ or $W_f = 1 - 1/(1 + W_d)$). With the exception of surface samples (W_f only), both values were computed to allow comparison with other studies. Bulk density (g cm^{-3}) was computed as the quotient of dry mass and fresh volume. Organic matter content (%) was computed as the quotient of the mass lost by LOI divided by dry mass. Ash-free density was computed as the quotient of the mass lost by LOI and fresh volume (g cm^{-3}). Any remaining fresh sample material was retained at the University of California, Los Angeles.

The numeric laboratory data were tabulated and cross-referenced with field notes on sample collection date, GPS coordinates, thaw depth (if permafrost was encountered) and depth to mineral substrate, to compile a finished database (see Supplementary material) on vertical soil moisture content, bulk properties and surface characteristics. For all 98 coring sites, summary statistics were calculated for each core in its entirety, as well as its upper and lower sections. The 'upper section' in permafrost cores was defined as all sample data collected within the thawed layer; in non-permafrost cores it was defined as all sample data collected within 30-cm depth of the surface. The 'lower section' in permafrost cores was defined as all sample data lying between basal peat (> 90% organic matter) and the base of the thawed layer; in non-permafrost cores it was defined as all sample data lying between basal peat (> 90% organic matter) and 30-cm depth. Using these criteria, summary statistics were obtained for 98 whole cores, 86 upper sections and 88 lower sections. Unpaired and paired t-tests were used to evaluate the statistical significance of differences between the population means of permafrost versus non-permafrost cores, and shallow versus deep-core material, respectively.

Total water storage in WSL peatlands (liquid equivalent) was computed as the product of gravimetric water content (whole-core means for permafrost and non-permafrost core populations) and peat mass as determined from historical Russian measurements of mean depth and mean bulk density merged with digitised map areas for 9691 peatlands across the region (Sheng *et al*., 2004). Peatland permafrost status was determined using the IPA's circumpolar map of permafrost and ground ice conditions (Brown *et al*., 1997, 2001). Continuous, discontinuous, sporadic and isolated patches of permafrost zones were generalised as 'permafrost-influenced' in accordance with previous WSL hydrology studies (Frey and Smith, 2005; Frey *et al*., 2007a, 2007b). All computations were performed in ArcGIS using the Lambert azimuthal equal-area map projection. For each peatland, water storages were computed in units of mass (Gt), liquid equivalent volume (km^3, assuming water density 1.0 g cm^{-3}) and liquid equivalent depth (cm, by dividing volume by GIS-mapped peatland area). Summation of these measures across all 9691 peatlands yields a first estimate for total subsurface water storage in WSL peatlands.

RESULTS

A total of 52 cores, ranging from 32 to 428 cm in depth, were obtained from permafrost peatlands and 46 cores, ranging from 30 to 542 cm in depth, were obtained from non-permafrost peatlands (Table 1; Figure 2). The complete database contains 13 308 data entries, of which 12 705 comprise vertical profiles of bulk soil properties (gravimetric water content W_f and W_d, bulk density, organic matter content and ash-free density; see whole-core averages in Table 1). Other data include 93 dominant living plant species assemblages, 152 observations of gravimetric surface moisture W_f, 97 observations of peat depth and 52 observations of thaw depth. Of the 46 non-permafrost cores, 34 were collected south of the WSL permafrost limit and 12 were collected from thawed low-lying swales called *mochazhiny* in Russian (designated with identifier 'M' in Table 1) located between frozen peat plateaus. These particular cores were located within tens of metres of known permafrost but were thawed throughout their depths and are thus treated as non-permafrost material for the purposes of this analysis. All other cores were collected from raised bogs and peat plateaus.

Summary statistics for all permafrost and all non-permafrost sites, including whole cores as well as their qualifying upper and lower sections, are presented in Table 2. Strong contrasts are found between permafrost and non-permafrost peat soils for all measured variables. On average, permafrost WSL peatlands exhibit lower gravimetric water content, lower organic matter content, shallower depth, higher bulk density and higher ash-free density than do non-permafrost WSL peatlands (Tables 1 and 2). Unpaired t-tests for whole cores confirm statistical significance of these contrasts across all variables with 99% confidence or better (Table 2). Similarly, strong contrasts are evident when comparing permafrost (versus non-permafrost) upper core sections and permafrost (versus non-permafrost) lower core sections. The sole exception is upper-section organic matter content, with no statistically significant difference found between thawed organic matter content in permafrost peatlands and the upper 30-cm organic matter content in non-permafrost peatlands (Table 2).

Statistically significant contrasts are also present between the moisture content of shallow versus deep peat ($p < 0.01$ in permafrost and $p < 0.0001$ in non-permafrost, Table 3). However, this phenomenon is opposed between the two populations, with permafrost sites displaying thawed layers that are drier relative to their subsurface. While the possibility of sampling-time bias cannot be eliminated, this contrast is preserved across many different collection sites over a three-year period, so is unlikely to be explained by antecedent rainfall, the timing of sample collection (all samples were collected in mid-July or later, after peak surface saturation from snowmelt) or other temporally variable moisture conditions. In absolute terms, permafrost peatlands have lower water content across all measures, with W_f, for example, averaging 81.6% in the thawed layer and 85.4% at depth, versus 92% and 89.3%, respectively, in upper and lower non-permafrost sites (Table 1).

Gravimetric surface moisture observations similarly indicate a strong contrast between the wetness of permafrost versus non-permafrost peatlands. Mean values of W_f are 72.0% and 81.3% in permafrost hummocks and swales, respectively, versus 88.5% and 93.6% in non-permafrost sites (Table 4). Surface moisture variability is also much higher in permafrost, as evidenced from higher standard deviations in Table 4 and Figure 1. Unpaired t-tests between permafrost and non-permafrost sample populations confirm this contrast to be statistically significant ($p < 0.0001$ or better).

In permafrost peat cores, no statistically significant contrast in organic matter content, bulk density or ash-free density is present between shallow and deeper peat materials. Consequently, the aforementioned surface dryness in permafrost peatlands cannot be attributed to vertical differences in bulk density (peat bulk density and water content are often inversely related). In non-permafrost peat, both bulk density and ash-free density are lower than their permafrost counterparts, and become denser at depth as well, averaging 0.066 and 0.025 g cm^{-3}, respectively, in the upper 30 cm and 0.104 and 0.101 g cm^{-3} in the subsurface ($p < 0.0001$, Table 3). The more fibrous upper-section peat materials in non-permafrost likely contribute to the higher moisture contents observed there. Of the variables measured, organic matter content is the only bulk soil property displaying no significant contrast between shallow and deeper peat materials in non-permafrost WSL peatlands.

A first mapping of WSL peatland water storage can be obtained by applying whole-core statistical means for permafrost and non-permafrost gravimetric water content ($W_d = 628 \pm 272\%$ for permafrost and $1027 \pm 313\%$ for non-permafrost, Table 1) to all 9691 WSL peatlands (Figure 2). In total, the WSL is estimated to contain some 1218 ± 448 Gt water mass, with approximately two-thirds of this mass residing in peatlands south of the permafrost limit (835 Gt versus 446 Gt in permafrost-influenced peatlands). This total storage is equivalent to 1218 ± 448-km^3 liquid water volume (water density 1.0 g cm^{-3}) and 205 ± 72-cm liquid equivalent depth if averaged across all peatlands of the WSL (Figure 1).

DISCUSSION AND CONCLUSION

The compiled peatland soil property database (see Supplementary material) adds to a growing collection of freely available digital datasets for peat and hydrologic properties of the WSL. Together with a GIS database (Sheng *et al.*, 2004), peat radiocarbon dates (including basal radiocarbon dates of the same cores presented here, see Smith *et al.*, 2004, auxiliary online material; Beilman *et al.*, 2009, Tables 1–3), river geochemistry (Frey *et al.*, 2007a, 2007b, auxiliary online material), river discharge (Shiklomanov *et al.*, 2007, www.R-ArcticNet.sr.unh.edu) and the geographic coordinates of 2161 field observations of land cover type (Frey and Smith, 2007, auxiliary online

Table 1 Summary description of 98 peat cores collected throughout the West Siberian Lowland (52 in permafrost, 46 in non-permafrost).

Core #	Date	Lat. N	Long. E	Depth (cm)	Thaw depth (cm)	W_f	W_d	OM	Bulk density	Ash-free density
N-1	21-Jul-99	63.161	74.823	242	20	86	666	99	0.12	0.12
N-2	22-Jul-99	63.881	75.023	61	36	84	655	96	0.10	0.09
N-10	2-Aug-99	63.141	76.536	120	30	84	607	98	0.13	0.13
N-12	3-Aug-99	63.500	76.817	216	30	83	551	89	0.14	0.13
N-13	4-Aug-99	63.771	76.643	159	20	76	413	90	0.24	0.16
N-14	5-Aug-99	63.772	75.511	81	30	84	670	99	0.14	0.14
N-15	5-Aug-99	63.650	74.269	213	30	89	1020	97	0.09	0.09
N-16	6-Aug-99	64.496	75.532	84	30	87	837	98	0.10	0.10
N-17	6-Aug-99	64.072	74.987	70	30	68	253	58	0.31	0.14
N-18	7-Aug-99	62.853	75.217	71	35	90	938	98	0.08	0.07
N-19	7-Aug-99	62.958	74.263	209	36	87	748	100	0.11	0.11
N-19-1	7-Aug-99	62.958	74.263	150	36	84	545	92	0.15	0.13
E-101	15-Jul-00	66.461	76.679	251	30	87	811	92	0.16	0.14
E-102	16-Jul-00	66.041	76.593	118	30	81	547	86	0.26	0.18
E-103	17-Jul-00	66.744	76.484	237	27	85	704	95	0.18	0.17
E-104	20-Jul-00	65.972	77.988	40	45	72	396	63	0.39	0.22
E-105	20-Jul-00	65.984	77.610	48	33	74	307	86	0.34	0.29
E-106	20-Jul-00	65.998	77.345	60	30	82	483	88	0.23	0.20
E-107	23-Jul-00	66.009	75.855	85	30	85	599	92	0.19	0.18
E-108	23-Jul-00	65.859	75.290	151	37	84	681	95	0.20	0.19
E-110	26-Jul-00	66.470	76.994	223	27	85	627	95	0.19	0.18
E-111	27-Jul-00	66.199	79.138	413	32	93	1763	95	0.09	0.09
E-112	28-Jul-00	66.199	79.139	90	27	83	532	87	0.22	0.19
E-113*	29-Jul-00	66.450	79.323	329	17	87	845	91	0.12	0.11
E-114	30-Jul-00	66.442	76.322	40	45–50	88	726	89	0.14	0.13
E-115*	31-Jul-00	67.809	75.435	99	21	75	359	73	0.23	0.16
E-116	31-Jul-00	67.464	76.422	45	24	69	240	54	0.42	0.18
E-118	2-Aug-00	66.602	77.411	53	30	72	358	79	0.39	0.25
E-119	3-Aug-00	65.500	75.502	312	30	86	762	92	0.20	0.14
E-120	4-Aug-00	65.608	77.961	76	28	86	625	95	0.18	0.17
E-121	5-Aug-00	65.865	78.814	31.5	27	80	402	97	0.18	0.17
D-122	8-Aug-00	65.583	73.006	108	40	81	475	84	0.24	0.20
D-123	9-Aug-00	64.422	71.031	118	42	83	575	96	0.20	0.19
D-124	10-Aug-00	65.084	72.970	95	28	82	504	98	0.19	0.19
D-125	11-Aug-00	64.523	72.162	231	25	86	681	94	0.16	0.16
D-126	13-Aug-00	64.332	71.204	56	50	68	224	95	0.34	0.32
D-127	14-Aug-00	64.307	70.295	228	50	88	858	95	0.14	0.13
D-128	15-Aug-00	65.550	72.463	229	30	91	1226	97	0.11	0.11
P-129	18-Aug-00	66.608	73.747	282	25	87	735	97	0.16	0.16
P-130	18-Aug-00	66.869	74.531	88	28	86	695	72	0.18	0.11
P-131*	19-Aug-00	66.166	73.989	127	30	80	451	91	0.17	0.14
P-132	20-Aug-00	66.500	73.949	81	42	82	545	90	0.22	0.19
P-133	20-Aug-00	65.793	74.348	428	38	89	1025	92	0.15	0.11
G-134	23-Aug-00	64.428	77.178	72	52	80	470	93	0.24	0.22
G-135	23-Aug-00	64.831	77.674	55	58	72	274	96	0.37	0.35
G-136	24-Aug-00	64.148	75.361	166	40	86	655	96	0.18	0.17
G-137*	24-Aug-00	63.750	75.766	177	50	87	833	97	0.13	0.11
G-138	25-Aug-00	64.517	76.673	142	48	88	856	96	0.15	0.15
G-139	25-Aug-00	64.889	76.730	84	58	73	313	59	0.38	0.19
G-140	26-Aug-00	64.271	79.548	117	45	77	413	88	0.31	0.22
G-141	27-Aug-00	64.688	75.402	63	38	87	821	97	0.16	0.15
G-142	27-Aug-00	64.090	78.595	72	58	78	378	94	0.27	0.25
S-4	24-Jul-99	61.546	72.715	125	—	89	898	99	0.09	0.09
S-5	24-Jul-99	61.977	72.181	88	—	90	952	97	0.09	0.09
S-6	25-Jul-99	61.618	73.978	252	—	89	867	97	0.10	0.09
S-7	26-Jul-99	61.487	74.316	272	—	91	1045	98	0.08	0.08
S-8	27-Jul-99	61.755	73.392	220	—	87	732	94	0.12	0.10

(*Continues*)

Table 1 (Continued)

Core #	Date	Lat. N	Long. E	Depth (cm)	Thaw depth (cm)	W_f	W_d	OM	Bulk density	Ash-free density
S-9	28-Jul-99	62.123	73.841	225	—	89	912	99	0.09	0.09
N-11	3-Aug-99	62.657	76.769	98	—	84	634	99	0.11	0.11
S-20	9-Aug-99	62.549	71.716	93	—	82	538	90	0.16	0.14
S-21	10-Aug-99	62.395	72.866	185	—	84	639	94	0.15	0.13
S-22	11-Aug-99	60.840	71.256	360	—	93	1425	98	0.06	0.06
S-23	12-Aug-99	60.653	73.080	200	—	91	1295	98	0.08	0.08
S-24	13-Aug-99	61.319	73.237	85	—	92	1716	97	0.08	0.07
S-25	13-Aug-99	62.255	74.777	135	—	85	601	97	0.13	0.13
V-26	15-Aug-99	61.029	76.469	447	—	92	1203	99	0.07	0.07
V-27	15-Aug-99	61.319	76.725	255	—	93	1465	94	0.06	0.06
V-28	16-Aug-99	61.808	77.503	542	—	94	1537	100	0.06	0.06
V-29	17-Aug-99	61.234	75.306	220	—	88	883	98	0.10	0.10
V-30	17-Aug-99	61.737	75.200	132	—	88	777	99	0.11	0.11
V-31	18-Aug-99	62.368	75.792	100	—	91	1215	96	0.08	0.08
V-32	19-Aug-99	62.359	77.477	108	—	92	1188	98	0.07	0.07
V-33	19-Aug-99	61.997	76.711	308	—	90	937	98	0.09	0.09
V-34	20-Aug-99	61.468	79.460	327	—	89	901	99	0.10	0.10
V-35	21-Aug-99	60.798	77.622	200	—	86	678	95	0.13	0.13
V-36	21-Aug-99	60.814	78.582	190	—	91	1426	98	0.08	0.08
V-37	22-Aug-99	61.246	74.725	218	—	90	944	72	0.09	0.06
V-38	22-Aug-99	60.804	74.542	308	—	91	1238	95	0.08	0.07
V-39	23-Aug-99	61.090	79.381	315	—	89	889	97	0.11	0.11
V-40	24-Aug-99	61.199	77.835	310	—	90	1055	99	0.09	0.09
E-118M	2-Aug-00	66.602	77.411	30	> 30	84	700	89	0.20	0.18
E-120M	4-Aug-00	65.608	77.961	n/a	> 60	78	383	74	0.30	0.22
E-121M	5-Aug-00	65.865	78.814	70	> 70	88	1070	94	0.16	0.15
D-123M	9-Aug-00	64.422	71.031	130	> 130	86	738	97	0.18	0.17
D-124M	10-Aug-00	65.084	72.970	110	> 110	91	1411	96	0.11	0.11
D-125M	11-Aug-00	64.523	72.162	225	> 225	89	855	95	0.14	0.13
D-126M	13-Aug-00	64.332	71.204	100	> 100	92	1609	93	0.11	0.10
D-127M	14-Aug-00	64.307	70.295	215	> 215	93	1377	97	0.09	0.09
G-136M	24-Aug-00	64.148	75.361	180	> 190	90	1036	91	0.12	0.11
G-139M	25-Aug-00	64.889	76.730	100	> 100	86	608	94	0.18	0.17
G-140M	26-Aug-00	64.271	79.548	160	> 160	86	899	89	0.18	0.13
G-142M	27-Aug-00	64.090	78.595	100	>100	91	1617	95	0.11	0.10
SIB01*	30-Jul-01	59.360	68.985	180	—	88	1047	94	0.11	0.08
SIB02*	2-Aug-01	61.055	70.059	280	—	90	997	99	0.09	0.09
SIB03*	4-Aug-01	56.355	79.069	300	—	90	1140	92	0.08	0.06
SIB04*	10-Aug-01	56.804	78.737	400	—	91	1209	95	0.09	0.07
SIB05*	12-Aug-01	57.354	81.164	165	—	89	982	95	0.09	0.09
SIB06*	14-Aug-01	58.436	83.434	395	—	90	981	98	0.09	0.08

Mean values for water content (W_f and W_d, %), organic matter content (OM, %), bulk density (g cm^{-3}) and ash-free density (g cm^{-3}) are averaged for all raw data down each core (see Supplementary material for full-resolution data). Most cores were sampled every 10 cm; select cores sampled every 1–2 cm are indicated by asterisks. n/a = Not available.

material), the data presented here provide a unique resource for hydrological and biogeochemical studies of the WSL.

The finding of (relatively) dry surface moisture conditions for peatlands underlain by permafrost is important for ongoing studies of hydrology and trace gas release from northern wetlands. A common assumption, based on observations of enhanced surface ponding, is that the hydraulic barrier created by permafrost prevents vertical drainage to the subsurface thus creating a wetter surface (Woo *et al*., 1992; Smith *et al*., 2005, 2007). The present study, however, suggests this hydraulic barrier may also operate in reverse, by limiting vertical wicking of subsurface liquid water to the uppermost peat column, thus promoting surface drying. This constraint on the upwards migration of subsurface water (e.g. Siegel *et al*., 1995) is not present in WSL non-permafrost peatlands, thus promoting persistently wet surfaces in mid- to late summer. Because our field campaigns began in mid-July, the current dataset cannot determine whether this relative contrast in soil moisture also occurs during late spring/early summer. But the *in-situ* data suggest that by the height of the WSL's growing and methane-production season, permafrost peatlands appear to be more susceptible to surface drying than do non-permafrost peatlands. This interpretation is further

Table 2 Comparison of permafrost (PF) and non-permafrost (Non-PF) core sample populations: whole core (all raw data), shallow core (all thaw data in PF, all upper 30-cm data in non-PF) and deep core (all data between shallow core and first basal peat horizon with organic matter >90%).

	Complete core					Upper section					Lower section				
	PF whole core (n = 52)		Non-PF whole core (n = 46)			PF thaw (n = 51)		Non-PF upper 30 cm (n = 35)			PF frozen below thaw (n = 45)		Non-PF below < 30 cm (n = 43)		
	mean	σ	mean	σ	*p*-value	mean	σ	mean	σ	*p*-value	mean	σ	Mean	σ	*p*-value
Moisture W_f (%)	82.4	6.1	88.9	3.2	< 0.0001	81.6	6.2	92.0	3.1	< 0.0001	85.4	4.3	89.3	2.9	< 0.0001
Moisture W_d (%)	628	272	1027	313	< 0.0001	548	239	1386	594	< 0.0001	716	296	1025	313	< 0.0001
Organic matter (%)	89.9	10.9	95.1	5.5	< 0.01	94.5	7.0	96.5	5.5	No	95.5	2.7	97.3	1.7	< 0.001
Bulk density (g cm^{-3})	0.201	0.087	0.110	0.044	< 0.0001	0.194	0.096	0.066	0.025	< 0.0001	0.160	0.047	0.104	0.032	< 0.0001
Ash-free density (g cm^{-3})	0.165	0.057	0.101	0.034	< 0.0001	0.179	0.084	0.063	0.021	< 0.0001	0.152	0.043	0.101	0.030	< 0.0001
Peat depth (cm)	142	95	210	111	< 0.01										
Thaw depth(cm)	35	10	—	—	—										

Measured soil properties include two computations of gravimetric water content, loss on ignition, dry peat bulk density and ash-free bulk density. Mean full-core depths and thaw depth (for PF only) are also shown. Unpaired t-test *p*-values indicate the probability that a statistically significant difference exists between PF and Non-PF core populations.

supported by gravimetric moisture data from live bryophyte samples which reveal generally lower and more variable surface moisture in permafrost than non-permafrost peatlands (Figure 1; Table 4). This finding has important implications for modelling studies and the up-scaling of eddy tower and other *in-situ* measurements, because it suggests that the presence or absence of permafrost should also be considered when estimating near-surface soil moisture and trace gas exchange with the atmosphere.

Interpretation of the contrasting bulk and ash-free densities between permafrost and non-permafrost peatlands is complicated by the different drilling methods required for frozen versus thawed terrain, and the tendency for pure ice lenses to drain from the thawing peat samples during transport. However, the observed contrast is also consistent with the presence of small groundcover plants (e.g. *Cladina* lichens) in the northern WSL, which tend to produce finer litter than larger *Sphagnum* species (Kremenetski *et al.*, 2003). The increase in density down-core in non-permafrost cores, but not in permafrost cores, is also consistent with ongoing deep decomposition in unfrozen peatlands but limited decomposition (below the thawed layer) in permafrost peatlands. Furthermore, observed lower bulk and ash-free densities in non-permafrost peatlands are consistent with a landscape-scale observation of surprisingly fast carbon accumulation rates in the southern WSL (Beilman *et al.*, 2009), as well as site-level patterns of carbon accumulation rates that are faster in unfrozen peat bogs and thawed internal lawns than in permafrost mounds (in western Canada, Turetsky *et al.*, 2007). However, it is important to note that WSL peatlands that are currently in permafrost may not all have been frozen throughout the Holocene, thus clouding simple comparisons between past decomposition and/or accumulation rates with the current permafrost state.

The estimated storage of ~1200 km^3 of liquid water equivalent in WSL peatlands is a large number, roughly triple the total annual flow in the Ob' River (~398 km^3 yr^{-1}, Shiklomanov *et al.*, 2006). Approximately two-thirds of this water resides south of the permafrost limit, where peatlands are deepest and their bulk densities lowest. Converted to liquid equivalent depth, some WSL peatlands hold more than 5 m of water (Figure 2), with a regionally averaged value of ~2 m. Such storages are at least one order of magnitude greater than interannual water table fluctuations measured in *Sphagnum*-dominated peatlands (e.g. typically 0–25 cm, Laitinen *et al.*, 2008).

Extrapolating this result to the entire circumpolar region, a first rough estimate of ~6900-km^3 liquid water equivalent total subsurface water storage in northern peatlands may be computed from published estimates of their land cover expanse (~4 million km^2, MacDonald *et al.*, 2006), mean depth (2.3 m, Gorham 1991), the mean bulk density of peat (0.091 g cm^{-3}, Turunen *et al.*, 2002) and mean peatland water content (e.g. W_d = ~828% based on this study). This number is conservative because our W_d data mainly come from raised bogs and peat plateaus, which are better drained than fens. In contrast, a rough estimate for the surface area

Table 3 Comparison of shallow ('Upper section') and deep ('Lower section') peat material for (a) all permafrost cores (n = 45); and (b) all non-permafrost cores (n = 34) with both upper and lower sections intact.

	Upper section		Lower section		*p*-value
(a)	mean	σ	mean	σ	
Moisture W_f (%)	82.1	5.7	85.4	4.3	< 0.01
Moisture W_d (%)	560	242	716	296	< 0.01
Organic matter (%)	95.2	5.6	95.5	2.7	Not sig.
Bulk density (g cm^{-3})	0.185	0.091	0.160	0.047	Not sig.
Ash-free density (g cm^{-3})	0.173	0.083	0.152	0.043	Not sig.
(b)					
Moisture W_f (%)	92.0	3.1	89.0	3.0	< 0.0001
Moisture W_d (%)	1390	602	987	305	< 0.0001
Organic matter (%)	96.6	5.5	97.5	1.5	Not sig.
Bulk density (g cm^{-3})	0.066	0.062	0.104	0.032	< 0.0001
Ash-free density (g cm^{-3})	0.025	0.021	0.101	0.031	< 0.0001

Paired t-test *p*-values indicate the probability that a statistically significant difference exists between shallow and deeper peat material.

Table 4 Gravimetric water content (W_f, %) of 152 live bryophyte surface samples from permafrost ($n = 102$) and non-permafrost ($n = 50$) West Siberian Lowland peatlands.

	Hummock		Swale	
	Mean W_f	*σ*	Mean W_f	*σ*
Permafrost	72.0	19.7	81.3	11.9
Non-permafrost	88.5	4.4	93.6	4.2
p-value	< 0.0001		< 0.001	

Unpaired *t*-test *p*-values indicate the probability that a statistically significant difference exists between PF and non-PF core populations.

of all lakes north of 45°N latitude is 1.188 million km^2 (Walter *et al*., 2007). Their mean depth is unknown, but employing an assumed value for average lake depth of 5 m (a large number, see Mellor, 1987; Duguay and Lafleur, 2003) would indicate ~5600 km^3 of total water storage in these lakes. These first-order estimates suggest that the interstitial pores of northern peatlands may store at least as much subsurface water (with about one-third currently frozen in permafrost) as do northern lakes.

For the WSL, this large water retention capacity, together with the freedom of vertical water movement in unfrozen peat, suggests that the disappearance of permafrost in the WSL could produce wetter peatland surfaces across the WSL, not drier ones, assuming no change in regional water balance (precipitation minus evapotranspiration). This conclusion is also consistent with a theoretical study modelling persistent wet conditions in peatlands even under regional air temperature increases of up to 9°C

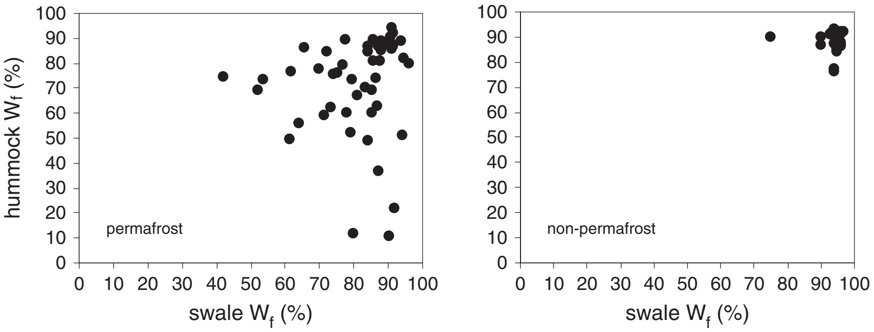

Figure 1 Adjacent hummock versus swale surface moisture for permafrost versus non-permafrost West Siberian Lowland peatlands. By July and August, non-permafrost sites display persistently moist surfaces relative to permafrost sites.

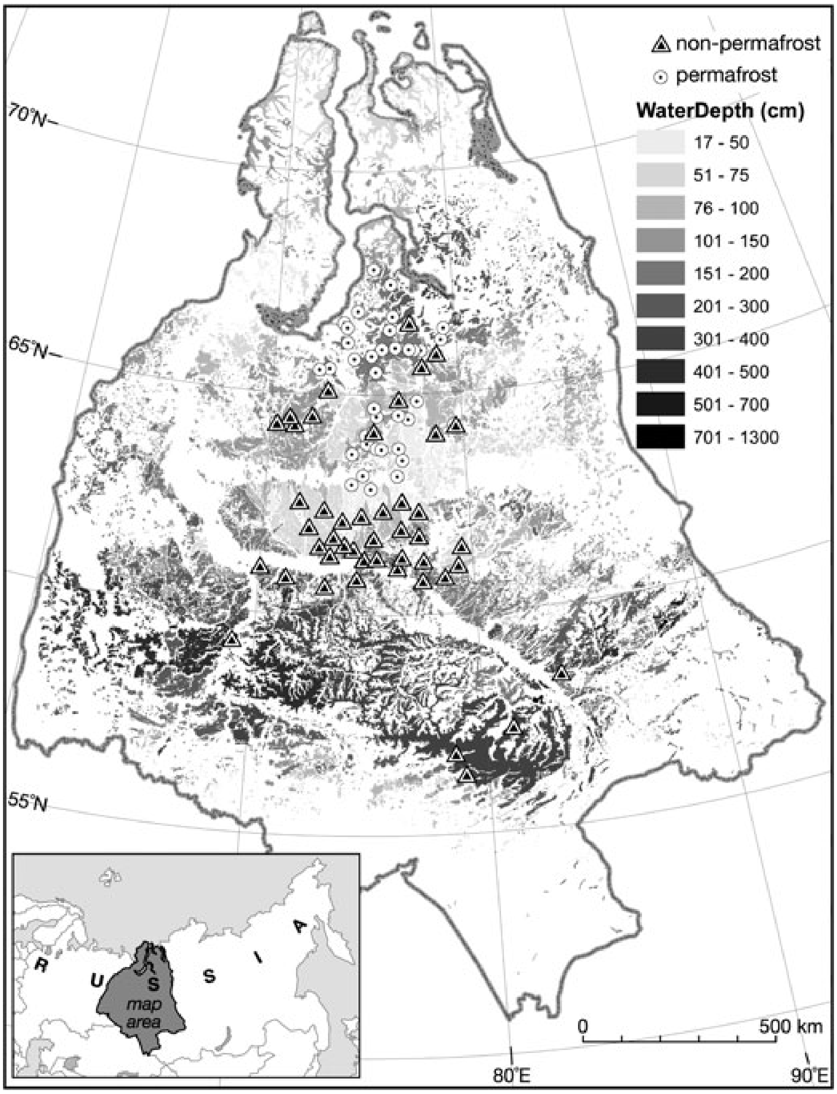

Figure 2 Estimated water storage of West Siberian Lowland peatlands (liquid equivalent depth). Total water mass is estimated as 1218 ± 448 Gt. Locations of permafrost (circles) and non-permafrost (triangles) coring sites are also shown.

(Wania *et al*., 2009). While the future status of any peatland as a carbon sink or a source to the atmosphere still hinges on the residual between net primary productivity and soil decomposition rate, a moister surface in newly thawed peatlands - especially when combined with warmer soil temperatures and invigorated anaerobic decomposition - would presumably favour enhanced methane production from the northernmost peatlands of West Siberia should deep permafrost thaw occur there in the future.

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