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Soil Organic Carbon Pools in a Periglacial Landscape: a Case Study from the Central Canadian Arctic

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ABSTRACT

We investigated total storage and landscape partitioning of soil organic carbon (SOC) in continuous permafrost terrain, central Canadian Arctic. The study is based on soil chemical analyses of pedons sampled to 1-m depth at 35 individual sites along three transects. Radiocarbon dating of cryoturbated soil pockets, basal peat and fossil wood shows that cryoturbation processes have been occurring since the Middle Holocene and that peat deposits started to accumulate in a forest-tundra environment where spruce was present (~6000 cal yrs BP). Detailed partitioning of SOC into surface organic horizons, cryoturbated soil pockets and non-cryoturbated mineral soil horizons is calculated (with storage in active layer and permafrost calculated separately) and explored using principal component analysis. The detailed partitioning and mean storage of SOC in the landscape are estimated from transect vegetation inventories and a land cover classification based on a Landsat satellite image. Mean SOC storage in the 0–100-cm depth interval is 33.8 kg C m^{-2}, of which 11.8 kg C m^{-2} is in permafrost. Fifty-six per cent of the total SOC mass is stored in peatlands (mainly bogs), but cryoturbated soil pockets in Turbic Cryosols also contribute significantly (17%). Elemental C/N ratios indicate that this cryoturbated soil organic matter (SOM) decomposes more slowly than SOM in surface O-horizons. Copyright © 2010 John Wiley & Sons, Ltd.

KEY WORDS: soil organic carbon pools; tundra land cover classification; peatlands; cryoturbation; permafrost

INTRODUCTION

High-latitude soils hold large stocks of soil organic carbon (SOC) and are an important component of the global C cycle. Much of this storage occurs in Cryosols and Histosols, where low temperatures and anoxia due to water-logging reduce decomposition rates (Davidson and Janssens, 2006). Based on the Northern Circumpolar Soil Carbon Database, Tarnocai *et al.* (2009) estimated SOC storage in the northern permafrost region (18 782 000 km^2, outlined by Brown *et al.*, 1997) to be 496 Pg ($Pg = g * 10^{15}$) for the top metre. Extending the depth to 3 m increased the estimate to 1024 Pg, with Histosols contributing 278 Pg and Cryosols 634 Pg. A substantial part of these stores is found in the Canadian Arctic. In the *Soil Organic Carbon of Canada*, map, Tarnocai and Lacelle (1996) estimated SOC storage in Canadian soils from the polygons in the *Soil Landscapes of Canada* database (Centre for Land and Biological Resources Research, 1996). They concluded that Organic and Cryosolic soils contained the largest total SOC masses, respectively storing 106 Pg and 103 Pg SOC (calculated to 1-m depth in mineral soils and to full depth in peat deposits; terminology following the Agriculture Canada Expert Committee on Soil Survey, 1987). Tarnocai (2006) subsequently updated the C-storage estimate for Canadian peatlands to 147 Pg SOC.

Gruber *et al.* (2004) identified permafrost soils and peatlands to be key C pools (together with oceans and forests) vulnerable to remobilisation through permafrost thaw and changed surface hydrological conditions. Across the northern hemisphere, there is a general trend of permafrost warming and active-layer thickening (Lemke *et al.*, 2007). Since the early 1990s permafrost temperatures in Canada have been rising (Brown *et al.*, 2000; Smith *et al.*, 2005). An acceleration of permafrost thaw has been observed in Canadian boreal peatlands (Camill, 2005). Tarnocai (2006) predicted that 60 per cent of Canada's peatlands (1.1 million km^2) would be severely or extremely severely affected by projected climate change.

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Despite previous research efforts, only generalised soil C inventories are available for large parts of the Canadian Arctic. In the central Canadian Arctic, the average polygon size in the *Soil Organic Carbon of Canada*, map is 25 000 km^2 (Tarnocai and Lacelle, 1996). The objective of this study was to assess the total storage and landscape distribution of SOC pools in an area of continuous permafrost terrain in the central Canadian Arctic, with detailed partitioning of active layer and permafrost SOC storage into surface organic soil horizons, cryoturbated soil pockets and mineral soil horizons. The results are discussed in the context of Holocene landscape development, outlining the timeframe and environmental conditions for SOC accumulation in the study area. The landscape allocation of SOC is assessed using a transect-based soil-sampling programme in a 22-km^2 study area. The results from SOC inventories are upscaled using transect vegetation inventories as well as full landscape upscaling using land cover data derived from Landsat satellite imagery. The degree of decomposition of soil organic matter (SOM) is assessed using C/N weight ratios. Basal peat and organic matter from cryoturbated soil horizons have been AMS ^{14}C dated.

STUDY AREA

The study area is located on the shore of Tulemalu Lake (62°55′N, 99°10′W, Figure 1), which lies in the Kazan Physiographic Region (Bostock, 1967). This area is part of the Canadian Shield, dominated by granitic bedrock and has been repeatedly glaciated. The landscape has a low topographic relief and the elevation in the study area ranges from 281 to 303 m a.s.l. (above sea level). Deglaciation of the Laurentide ice sheet in this region occurred between 9000–8000 cal yrs BP (Dyke and Prest, 1987a, 1987b). Quaternary deposits consist of glacial till with sandy loam to loamy sand texture and sandy-textured glaciofluvial materials. Peat deposits (partially decomposed plant remains, with or without admixtures of sand, silt or clay) have accumulated in depressions throughout the study area.

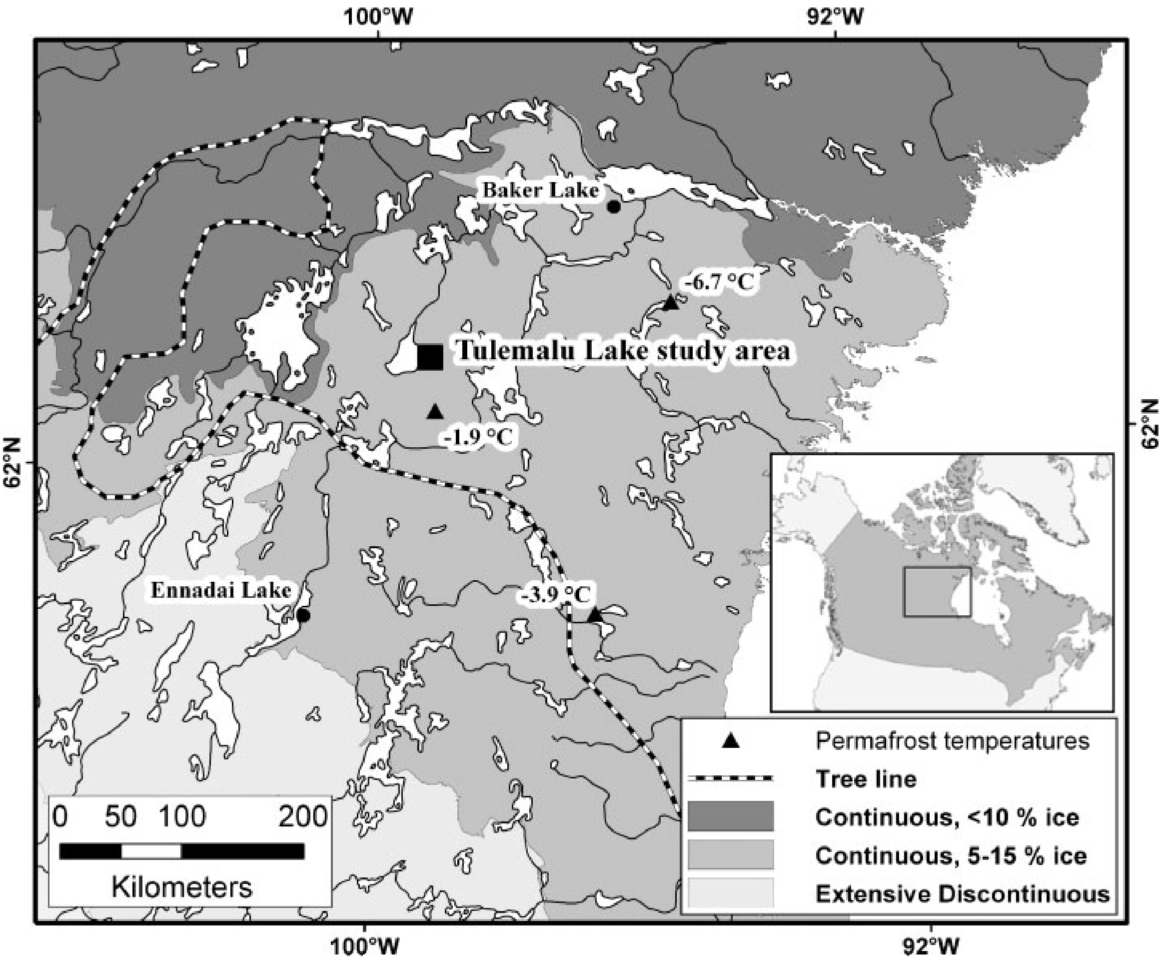

Figure 1 Overview map showing the location of the Tulemalu Lake study area in relation to hydrography, treeline and permafrost zonation in southern Nunavut. Map also shows the location of the nearest climate stations and permafrost temperatures. Data on permafrost zonation from Canada's *EcoATLAS* (Government of Canada, 1998). Treeline and permafrost temperatures are from Brown *et al*. (1997).

The regional climate is continental with a high annual temperature range and low precipitation. Figure 1 shows the locations of the climate stations nearest to Tulemalu Lake: Ennadai Lake (61°08′N, 100°54′W, 325 m a.s.l.) and Baker Lake (64°30′N, 96°08′W, 18 m a.s.l.). Mean Annual Air Temperature (MAAT) ranges from −9.4°C to −14.3°C and total annual precipitation is less than 300 mm. Precipitation in the cold months (mean temperature <0°C) represents less than 40 per cent of the annual total; mean maximum snow depths are 40–50 cm. The region is part of the continuous permafrost zone, with low to medium ice content. Mean annual ground temperatures at the depth of zero annual amplitude are between −1.9°C and −6.7°C and permafrost extends down to 400 m (Figure 1: Heginbottom *et al.*, 1995; Brown *et al*., 1997).

Tulemalu Lake is located in the Low Arctic zone (Ecoregions Working Group, 1989). The northernmost spruce trees grow 50–75 km south from our study area, with larger forest stands found 100 km southwards (treeline from Brown *et al*., 1997, in Figure 1). The border for contiguous taiga is located 200 km to the south, at the latitude of Ennadai Lake. The vegetation at Tulemalu Lake consists of a mosaic of shrub tundra and peatlands following moisture gradients in the landscape. Shrub tundra with willow (*Salix*) and dwarf *Betula* shrubs dominates on loamy till soils, ranging from wet to dry depending on catenary position. Dry lichen (*Cladonia*) tundra with some *Empetrum* and *Vaccinium* shrubs is found on sandy, well-drained soils. Bogs with high-centre ice-wedge polygons are dominated by mosses, lichen, prostrate shrubs (*Vaccinium* spp. and *Ledum palustre*) and *Rubus chamaemorus*. Fens are characterised by graminoids (*Eriophorum* spp.), with *Drepanocladus* spp. and *Sphagnum* spp. mosses.

MATERIALS AND METHODS

Field Sampling

Soils were sampled along three 1-km transects. The transects were chosen to represent the main vegetation types and geomorphology of the landscape based on field reconnaissance. Once the transects were established, soil samples were collected at 100 m intervals without further subjective bias. This sampling scheme combined selective representation with a measure of randomisation introduced by small-scale vegetation and micro-topography patterns. Two sampling locations fell on borders between different vegetation types, and there, two separate pedons were described. A total of 35 sites were described and sampled and 334 individual soil samples were collected and analysed. Sampling included upland soils (to 1-m depth) and peat deposits (to 1-m depth or full depth of peat deposits). Full soil pits were dug at 16 sites and each soil horizon was sampled and described. At the remaining 19 sites, samples were collected using a steel pipe hammered into the ground. To capture some of the micro-topographic variability in hummocky terrain, three replicate samples of the topmost organic layer were collected and analysed (but not in peatland sites). All soils were classified following the *World Reference Base of Soil Terminology* (WRB) (IUSS Working Group WRB, 2006) and *The Canadian System of Soil Classification* (Soil Classification Working Group, 1998).

The depth of the frost table was recorded at all sites. As sampling was performed in August (7–15 August 2006), before maximum annual thaw is reached, this does not correspond to the active-layer depth. However, for the purpose of the SOC storage discussion, we refer to unfrozen and frozen soil horizons in terms of active layer and permafrost.

Radiocarbon Dating and Soil Chemical Analyses

A total of 14 samples were submitted for AMS ^{14}C dating at the Poznan Radiocarbon Laboratory, Poland. Basal organics (bulk material, with roots removed under a microscope) were extracted from three wet shrub tundra sites, three fen peatlands and three bog peatlands. Three samples from cryoturbated soil horizons were dated. The remains of a spruce tree trunk found in a thermokarst pond at the site TL 2-7B were also ^{14}C dated. At site TL 4-1 a palaeosol profile was found under a layer of sand in the shoreline on Tulemalu Lake. The organic horizon of this palaeosol was submitted for ^{14}C dating.

Samples from all 35 sites were analysed for dry bulk density (BD, g/cm^3) after oven drying at 95°C (for 24 h). Loss on ignition (LOI, weight %) at 550°C (for 6 h) was used to determine organic content, and at 950°C (for 2 h) to determine carbonate content (Dean, 1974; Heiri *et al*., 2001). For sites where soil pits were dug (n = 16), each soil horizon was analysed, while for other sites (n = 19) analyses were performed in 10-cm depth increments. For samples from the 16 soil pits, soil pH was measured in a 1:2 solution of $CaCl_2$ (0.01 M). A subset of samples, selected to be representative of the landscape as a whole, was run in an elemental analyser (CE-instruments, EA 1110) to determine organic C and N content (n = 114). The carbon/nitrogen (C/N) ratio is a useful indicator of decomposition of SOM (Kuhry and Vitt, 1996; McKane *et al*., 1997).

A third-order polynomial regression model based on individual soil samples where both LOI and C per cent were available (n = 94, $R^2 = 0.97$) was used to predict C per cent for the soil samples where only LOI was available (n = 220):

$$Y = -0.6245x^3 + 0.7185x^2 + 0.355x + 0.0029 \qquad (1)$$

Calculating SOC Partitioning and Storage

SOC storage (kg C m^{-2}) for each sampled soil horizon (cm) was calculated from the BD (g/cm^{-3}), fraction organic C, fraction coarse fragments (>2 mm diameter: CF) and depth (cm) of the sampled horizon using:

$$SOC = (BD * C * (1 - CF) * depth) * 10 \qquad (2)$$

Site SOC storage ($kg\,C\,m^{-2}$) was calculated for two reference depths: 30-cm depth (SOC 0–30 cm) and 100 cm depth (SOC 0–100 cm). To describe the partitioning of SOC in each site, SOC storage was calculated separately for surface organic horizons (using the mean SOC storage and depth from the three replicate samples for non-peatland sites), cryoturbated soil pockets and non-cryoturbated mineral horizons. SOC storage for these three groups was further separated into storage above and below the frost table. The surface organic layers included organic horizons in non-histosols (folic or histic horizons) and the histic horizon of Histosols (peat and gyttja deposits).

For the 16 excavated soil pits, SOC storage in cryoturbated mineral and organic pockets was calculated based on scaled drawings of soil pits (Kimble *et al*., 1993). For the 19 sites that were sampled through coring, cryoturbated soil pockets with elevated organic content were separated from the mineral subsoil based on the colour and texture of extracted samples. We may have failed to recognise some turbic horizons without enrichment of SOM in the cored samples, but since these have a low organic content they would contribute little to the total C storage in deeper cryoturbated soil pockets. Mineral horizons included all mineral subsoil without any recognisable signs of cryoturbation. In the laboratory, the samples identified as cryoturbated soil pockets had a mean C content of 3.2 per cent (range 0.07%–30.3%), while the mineral non-cryoturbated samples had a mean C content of 0.45 per cent (range 0.02–1.09%).

Statistical Analyses

C/N ratios of different types of soil material were compared using Student t-tests performed in the software PAST (Hammer *et al*., 2001). Principal component analysis (PCA; software CANOCO 4.5, Ter Braak and Smilauer, 2002) was used to illustrate patterns in C-storage partitioning at site level. All variables expressed as percentages or quotas were arcsin-transformed to decrease the influence of extreme values. The gradient length of the dataset was calculated in detrended correspondence analysis to 1.068, confirming that the dataset shows linear responses suitable for analyses in PCA (Jongman *et al*., 1995, p. 154). The dataset was standardised to zero mean and unit variance to enable comparisons between variables expressed in different units and on different scales of measurement.

Landscape Classification and Upscaling

To enable interpretation and landscape upscaling of sampling results, we inventoried the land cover along the sampled transects and mapped land cover in the larger surrounding area. The vegetation inventories were done in the field by walking along the sampled transects, recording the vegetation and classifying segments into different land cover types. A land cover classification (LCC) based on Landsat 7 ETM+ imagery (path 36, row 16, date 2 August 2000, 30-m pixel size) was produced with a supervised classification methodology (maximum-likelihood classification using spectral bands 2–5 and 7). Training areas for the different land cover classes were defined using ERDAS IMAGINE's interactive seed pixel region-growing technique (Leica Geosystems, 2005, p. 250).

The LCC was verified using 86 independent ground-truthing points (33 transect points sampled for soil C and 53 random points). Land cover types and vegetation were described in the field for a 5-m radius around each ground-truthing point. Points were classified into seven LCC classes. The classification was considered correct if a correctly classified pixel fell within this area. The entire classification covers 403 km^2, of which 143 km^2 is water (LCC region). We focused our landscape upscaling on a smaller (42 km^2) study area, delineated to be representative of the sampled area. A total of 20 km^2 of the area is water and this was excluded from upscaling, leaving 22.1 km^2 of terrestrial habitats (LCC study area).

Mean SOC storage ($kg\ C\ m^{-2}$) for each vegetation class was calculated as the arithmetic mean of SOC storage in the sites belonging to that class. For transect upscaling, the soil-sampling results were upscaled according to the proportional representation of land cover types along the inventoried transects. For the landscape upscaling, we used percentage coverage from the LCC.

RESULTS

LCC

The overall accuracy of the LCC is 78 per cent and the kappa index of agreement is 0.71. If the three shrub tundra classes are amalgamated into one class, the values increase to 85 per cent and 0.79, respectively. Table 1 summarises the percentage coverage of the different land cover types in sampling, transect coverage, the LCC study area (map in Figure 2) and the LCC region and also shows which soil types were typically underlying each land cover type. The land cover type bare ground (not sampled) is only represented in the LCC. This occurs only on exposed sandy beaches and is unlikely to contain significant amounts of SOC.

Soils and Cryoturbation

Appendix 1 contains a table summarising some properties of the 16 sites where full soil pits were sampled and described. Soils developed on sandy loam to loamy sand-textured glacial till are mainly Turbic (sometimes Histic) Cryosols. The soils have a thaw depth of less than 1 m and are often associated with non-sorted circles and ice-wedge polygons. The high amount of silt/loam in these soils favours cryoturbation processes (Washburn, 1980), resulting in

Table 1 Percentage land cover type representation in the sampling programme, transect inventory, LCC study area and LCC region (water excluded), as well as major WRB soil classification for soils underlying the vegetation types at sampled sites.

Land cover	Sites *n*/	Land cover representation (%)				Soil classification WRB
		Samples	Transects	LCC study area	LCC region	
Fen peatland	7	20%	22%	21%	25%	Histic Cryosol *or* Cryic Histosol
Bog peatland	3	9%	21%	16%	16%	Cryic Hemic Histosol
Wet shrub tundra	5	14%	14%	15%	13%	Turbic (Histic) Cryosol
Moist shrub tundra	12	34%	30%	35%	31%	Turbic Cryosol
Dry shrub tundra	5	14%	9%	9%	9%	Turbic Cryosol
Lichen tundra	3	9%	4%	2%	5%	Haplic (Cambic) Cryosol
Bare ground	—	—	—	2%	1%	—

Note: Soil diagnostic criteria present at a few sites are included in brackets while diagnostic criteria present at only one site are excluded. Abbreviations are defined in the text. Abbreviations are defined in the text.

frost-heaved stones, movement of soil materials and the formation of patterned ground. Cryoturbated soils are found from well-drained upper catenary positions to poorly drained lower catenary positions. These soils are strongly to very strongly acidic (pH 4.5–5.2) and generally low in nitrogen. Vegetation overlying Turbic Cryosols is typically shrub tundra; altogether, 16 out of 22 sites with shrub tundra vegetation developed on till soils are cryoturbated.

Soils developed on sandy-textured glaciofluvial materials are generally non-cryoturbated Cambic or Haplic Cryosols.

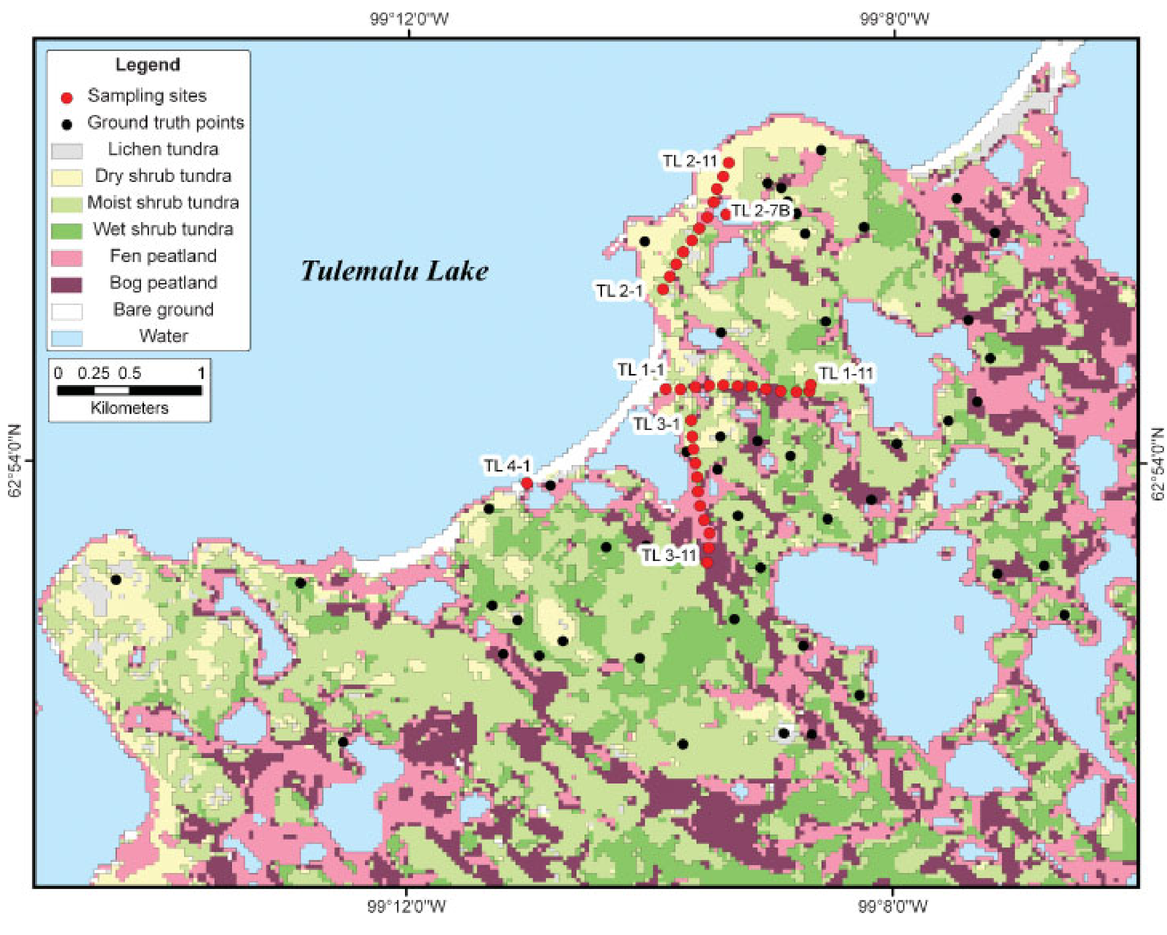

Figure 2 Map of the LCC study area showing general land cover distribution, location of transects with sampling sites and ground-truth points (many ground-truth points were located outside the LCC study area). The first and last points in transects as well as TL 2-7B (fossil wood) and TL 4-1 (palaeosol) are labelled. Projection UTM zone 14N (WGS 84). Abbreviation is defined in the text.

Table 2 Table summarising results of radiocarbon dating.

Site	Depth	Vegetation/Sample description	Age ^{14}C BP	Age cal BP[a]	Lab. no.[b]
		Cryoturbated soil pockets			
TL 2-4	60–62 cm	Moist shrub tundra, Ahy-horizon[c]	5690 ± 35	6470	Poz-19645
TL 3-1	27–28 cm	Wet shrub tundra, Ohy-horizon	2450 ± 30	2670	Poz-18616
TL 3-1	80–90 cm	Wet shrub tundra, Ahy-horizon	3850 ± 35	4260	Poz-18617
		Base of surface organic layer			
TL 1-3	32–35 cm	Wet shrub tundra, base of surface organic layer	3680 ± 35	4030	Poz-19689
TL 1-8	32–35 cm	Wet shrub tundra, base of surface organic layer	3265 ± 35	3530	Poz-19688
TL 2-8	32–33 cm	Wet shrub tundra, base of surface organic layer	3190 ± 40	3420	Poz-18675
		Base of peat deposits			
TL 2-6	47–48 cm	Wet fen, basal peat (underlain by gyttja)	3630 ± 50	3925	Poz-18673
TL 3-5	30–32 cm	Wet fen, base of gyttja deposit	1405 ± 30	1300	Poz-19647
TL 3-6	27–28 cm	Wet fen, base of gyttja deposit	1015 ± 30	940	Poz-18676
TL 2-2	34–36 cm	Dry bog, basal peat (underlain by gyttja)	5220 ± 50	5955	Poz-19687
TL 2-7	90–100 cm	Dry bog, basal peat	3490 ± 35	3735	Poz-18615
TL 3-11	95–100 cm	Dry bog, basal peat	4700 ± 40	5365	Poz-18677
		Other			
TL 4-1	49–54 cm	Tulemalu Lake shoreline, palaeosol	4525 ± 35	5155	Poz-18618
TL 2-7B	—	Fossil spruce tree found in lake bottom	5060 ± 40	5845	Poz-18674

[a] Indicated age is the highest probability interval median expressed as calendar years before 1950, calibrated using OxCal 3.
[b] Laboratory number at the Poznan Radiocarbon Laboratory.
[c] Terminology following *The Canadian System of Soil Classification* (Soil Classification Working Group, 1998).

These soils have active layers less than 1 m and are often associated with ice-wedge polygons. The vegetation is typically dry lichen tundra with some prostrate shrubs.

Soils associated with bog peatlands are Cryic Hemic Histosols with active layers ranging between 30 and 60 cm. Bog peat deposits are located in association with lowland ice-wedge polygons. The investigated bog peat deposits are underlain by sand and showed no sign of cryoturbation processes. The sampled fen peatlands are mainly Histic Cryosols (shallow gyttja deposits overlying till with some signs of frost-heaved stones, n = 6) with one Cryic Hemic Histosol (thicker fen peat deposit).

Radiocarbon Dating

Table 2 summarises the results of AMS ^{14}C dating. All ^{14}C-dated cryoturbated soil pockets are in Turbic Cryosols underlying shrub tundra vegetation. The ages of cryoturbated SOM (6470, 4260 and 2670 cal yrs BP) indicate that cryoturbation processes have been occurring in the study area over at least several millennia. The two younger ages are from the same pedon (TL 3-1), showing repeated burial of SOM at the same site. The two shallow fens (TL 3-5 and TL 3-6) have young basal ages of 1300 and 940 cal yrs BP. The organic deposits in these fens (together with the fens in TL 3-7 through TL 3-10) have thin layers of peat overlying deposits of gyttja. The base of the 54-cm fen peat deposit at TL 2-6 is older (3925 cal yrs BP), corresponding to the basal age of the nearby bog at TL 2-7 (3735 cal yrs BP). The bogs at TL 2-2 and TL 3-11 have older basal ages (5955 and 5355 cal yrs BP). The fossil spruce wood (TL 2-7B) is dated to 5845 cal yrs BP, and the palaeosol (TL 4-1) in the shoreline of Tulemalu Lake to 5155 cal yrs BP.

Soil Chemical Analyses

Generally, low LOI values at 950°C (mean = 1.1%) indicate that very little inorganic C (carbonate) is stored in the soils of the study area. Figure 3 shows C/N weight ratios separately for Turbic Cryosols and peatlands (Histosols and Histic Cryosols). There is generally little variance in the C/N data, with few values outside the range of 12–20. Peat samples generally show relatively low C/N ratios consistent with fen peat in the Arctic ecoclimatic region (Vardy *et al.*, 2000).

Student t-tests were used to see if the groups of C/N ratios differed between substrate types. For the Turbic Cryosols, the C/N ratios of surface organic horizons (n = 21) and cryoturbated soil pockets (n = 13) samples show no statistical difference ($p = 0.4$), but they are both significantly higher than C/N ratios of mineral soil horizons (n = 16) ($p = 0.01$ and $p < 0.01$, respectively). For peatlands, there is no significant difference between C/N ratios of peat samples (n = 33) and gyttja samples (n = 10) ($p = 0.12$). Mineral samples underlying peatlands were not tested as only two C/N values were available from such samples.

PCA of SOC Partitioning in Pedon Profiles

The ordination diagram in Figure 4 shows the first and second principal components (PC) of a PCA focused on

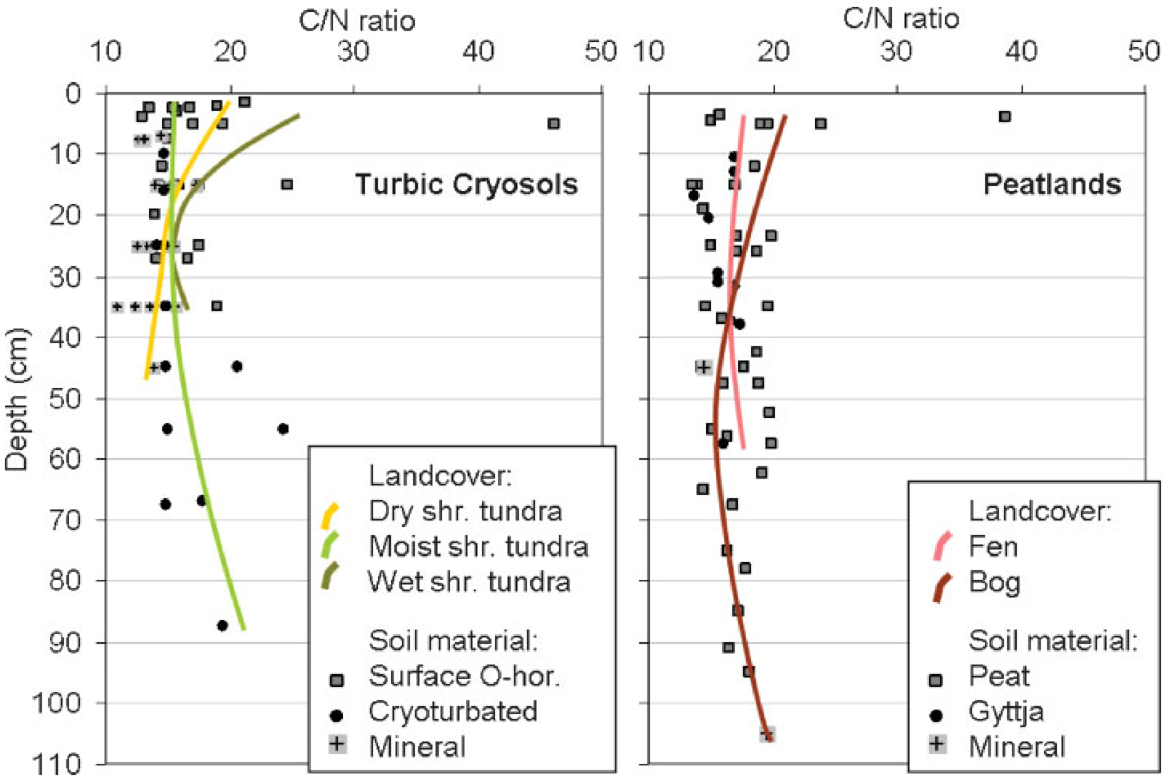

Figure 3 Graphs show C/N weight ratios presented separately for Turbic Cryosols and peatlands. Coloured lines show trends for the separate land cover classes (based on second-degree polynomial regressions). Grey-scale symbols show separate samples of different horizons (top organics, cryoturbated pockets and non-cryoturbated mineral in Turbic Cryosols, and peat, gyttja and mineral in peatlands).

proportional SOC storage ($_pC$) within the active layer and permafrost in organic soil horizons, cryoturbated soil pockets and non-cryoturbated mineral soil horizons at all 35 sites (sites shown as symbols). Supplementary environmental variables (SOC 0–100 cm storage, BD, thickness of surface organic deposits and frost table) are shown with arrows.

High total SOC storage (SOC 0–100 cm) is associated with thick surface organic deposits and a shallow frost table. These variables are in turn negatively correlated to mean BD. There is a relatively small spread among peatland sites. Fen sites store a large proportion of SOC in, mainly unfrozen organic horizons (gyttja deposits) and frozen mineral horizons. The bogs show little variation and are associated with thick surface organic layers and a high frost table.

There is large variation in the distribution of shrub tundra sites in the ordination. Wet shrub tundra sites are spread out perpendicularly to the SOC 0–100 cm storage vector. While they all have relatively high SOC 0–100 cm storage it is concentrated in either thick surface organic soil horizons (to the right) or cryoturbated soil pockets (upper left). Moist and dry shrub tundra sites have low variation along PC1, indicating little variability of SOC storage in surface organic horizons (one dry shrub tundra site breaks this pattern: TL 2-11 with 7 kg C m^{-2} in the surface organic horizon). However, there is a larger variation along PC2, reflecting varying SOC storage in cryoturbated soil pockets. Tundra sites with a large proportion of SOC stored in cryoturbated soil pockets (upper left) are also associated with higher total SOC 0–100 cm storage than sites with no cryoturbation (lower left). All three lichen tundra sites (developed on sandy soils) have high BD and low SOC 0–100 cm storage, with the majority of SOC stored in non-cryoturbated mineral horizons.

Total C Storage and Landscape Partitioning

The arithmetic mean of SOC 0–100 cm storage in all 35 sites is 28.6 kg C m^{-2}. Table 3 provides a summary of SOC storage and partitioning based on LCC (study area) upscaling. Mean SOC 0–100 cm storage in the study area is 33.8 kg C m^{-2}, of which 16.3 kg C m^{-2} is in the top 30 cm. Surface organic layers (including peat and gyttja deposits) hold a total of 22.2 kg C m^{-2}, cryoturbated soil pockets store 5.8 kg C m^{-2} with the remaining 5.8 kg C m^{-2} stored in non-cryoturbated mineral soil horizons. About a third of all SOC in the top metre (11.8 kg C m^{-2}) is stored below the active layer in permafrost.

If storage is calculated using transect-based upscaling, the estimated mean SOC storage increases to 37.1 kg C m^{-2}, with 17.6 kg C m^{-2} in the top 30 cm. The transect upscaling estimates surface organic deposits to 26.2 kg C m^{-2},

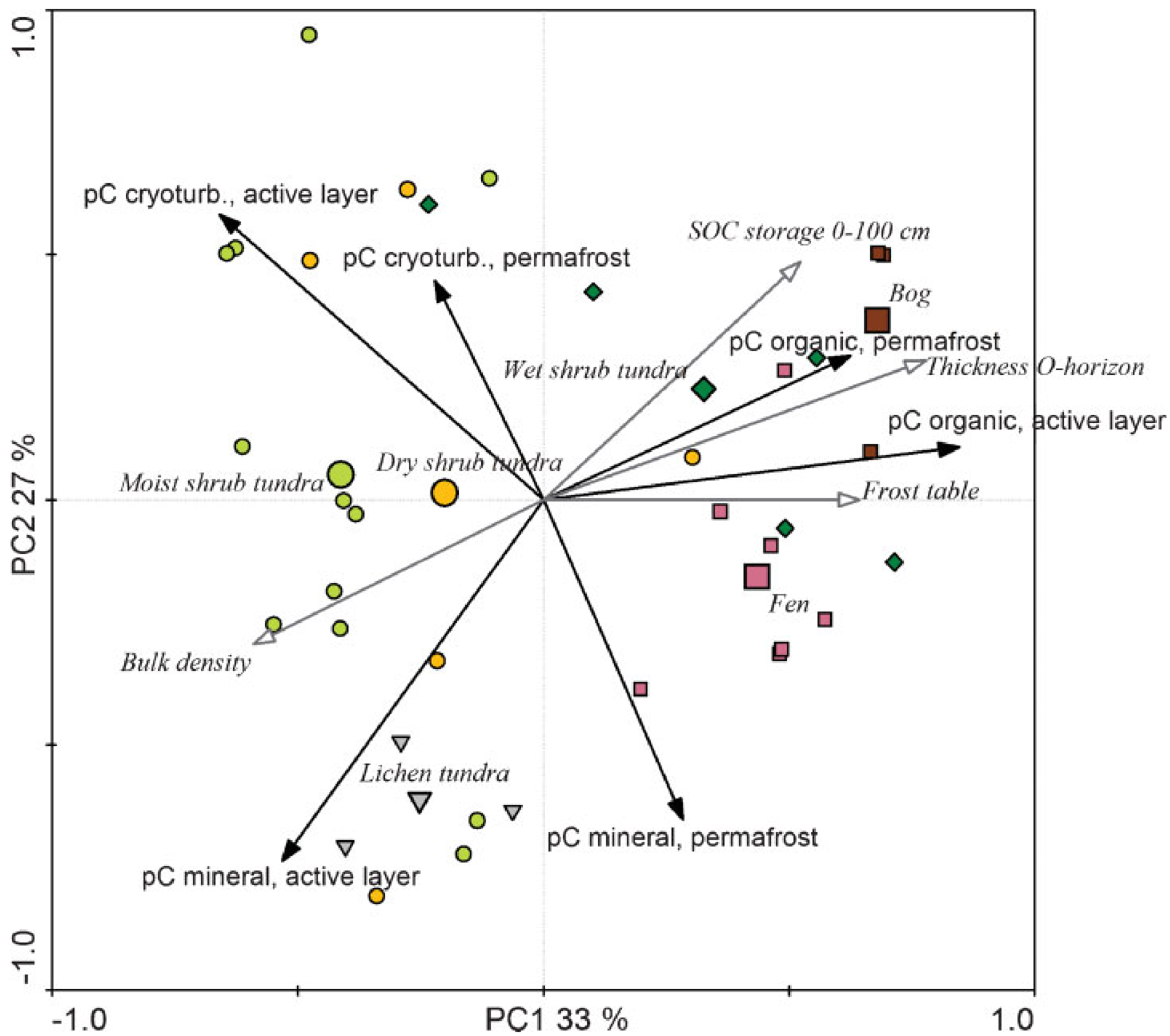

Figure 4 PCA ordination diagram showing partitioning of SOC storage. Black arrows show the main variables controlling ordination. Italic labels with grey arrows signify supplementary variables not affecting ordination (SOC 0–100 cm storage as kg C m^{-2}, bulk density, thickness of surface O-horizons (including peat deposits) and depth of the frost table). Coloured symbols show the individual sites, according to land cover class. The centroid for each land cover class is shown with a larger symbol (labelled). Abbreviations are defined in the text.

cryoturbated pockets to 5.3 kg C m^{-2} and non-cryoturbated mineral horizons to 5.6 kg C m^{-2}. Permafrost SOC storage is estimated to be 13.8 kg C m^{-2}.

Average SOC storage and peat thickness in bogs are considerably higher than in fen peatlands. The mean depth and SOC storage in surface organic horizons of tundra vegetation types increase gradually along the moisture gradient: there is a near doubling of SOC storage from dry to moist shrub tundra and again from moist to wet shrub tundra. All shrub tundra classes store significant amounts of SOC in cryoturbated soil pockets.

Based on the LCC, total storage of SOC (0–100 cm) in the 22.1 km^2 study area is estimated at ~750 kt (lakes excluded). Figure 5 shows the partitioning of this SOC, divided according to land cover type and storage in different types of deposits.

DISCUSSION

Holocene Landscape Development

Deglaciation of the Laurentide ice sheet occurred in the study area between 9000–8000 cal yrs BP (Dyke and Prest, 1987a, 1987b). Warmer than present climatic conditions prevailed in the region during the Middle Holocene. A radiocarbon date from fossil spruce wood found in a shallow lake at TL2-7B shows that trees were present in the Tulemalu study area at 5845 cal yrs BP. This coincides with evidence from a palaeoecological reconstruction by MacDonald *et al*. (1993) who recorded a marked advance of the spruce treeline at 5700 cal yrs BP at a site 150 km NW of our study area. Presently, northernmost spruce trees are growing 50–75 km south of our study area. The palaeosol profile at

Table 3 Summary of mean C storage ($kg\,C\,m^{-2}$) by land cover class in the following categories: 0–100-cm depth, 0–30-cm depth and 30–100-cm depth in surface organic horizons, cryoturbated soils horizons and stored in permafrost (including all frozen soil horizons regardless of type). The table also lists the mean depth of surface organic deposits and the mean position of the frost table at the time of sampling.

Land cover (n: sites)		Mean soil organic C storage ($kg\,C\,m^{-2}$)							Mean depth (cm)	
		C 0–100 cm	C 0–30 cm	C 30–100 cm	Top org.	Cryoturb.	Mineral	Permafrost	Top O-horizon	Frost table[c]
Bog peatland[a] (n: 3)	Mean: StD:	81.7 ± 24.7	35.2 ± 2.4	46.6 ± 22.4	79.9 ± 27.7	—	1.8 ± 3.1	42.9 ± 21.4	92 ± 23.6	33 ± 0.6
Fen peatland[b] (n: 7)	Mean: StD:	27.7 ± 9.7	16.8 ± 2.0	10.9 ± 8.6	21.5 ± 9.8	—	6.2 ± 3.1	6.4 ± 8.4	38 ± 12.6	57 ± 17.9
Wet shrub tundra (n: 5)	Mean: StD:	40.3 ± 9.8	20.6 ± 4.1	19.8 ± 10.9	22.0 ± 6.8	11.1 ± 13.1	7.2 ± 8.4	15.2 ± 15.4	24 ± 5.7	50 ± 37.5
Moist shrub tundra (n: 12)	Mean: StD:	21.2 ± 9.4	9.8 ± 5.2	11.4 ± 6.0	3.7 ± 2.2	10.2 ± 10.9	7.3 ± 5.1	3.3 ± 5.0	5 ± 3.9	>77 ± 16.5
Dry shrub tundra (n: 5)	Mean: StD:	13.9 ± 8.4	6.0 ± 3.0	7.9 ± 6.1	3.6 ± 2.5	6.1 ± 9.6	4.2 ± 4.1	1.1 ± 1.6	5 ± 4.3	> 83 ± 10.6
Lichen tundra (n: 3)	Mean: StD:	11.9 ± 5.7	4.8 ± 3.5	7.0 ± 6.0	1.9 ± 1.8	—	10.0 ± 5.0	1.4 ± 1.2	4 ± 2.7	86 ± 10.2
Study area	Mean:	33.8	16.3	17.5	22.2	5.8	5.8	11.8	22	67

Note: Land cover type bare ground was not sampled and is not included.
[a] Includes one bog peatland site where the peat deposit ends at 105-cm depth and including gyttja deposits.
[b] Including gyttja deposits.
[c] Five moist shrub tundra sites and two dry shrub tundra sites had no permafrost in the top metre (set to 100 cm in calculations).

the shore of Tulemalu Lake (site TL 4-1A) shows that the water level in the big lake has not been much higher than present since at least 5155 cal yrs BP.

Radiocarbon dating of deep cryoturbated SOM (6470, 4260 and 2670 cal yrs BP) shows that cryoturbation processes were active in the Middle and Late Holocene. Cryoturbation dated to ~6500 cal yrs BP, during the Holocene warm period, suggests that permafrost was present in the area at that time. This is supported by findings from Zoltai (1995) who mapped permafrost distribution in peatlands of west-central Canada for 6800 cal yrs BP. Tulemalu Lake is located just to the north of Zoltai's (1995) estimated 6800 cal yrs BP border of continuous permafrost.

The oldest basal peat, ~6000 cal yrs BP (site TL 2-2), is from a shallow bog peat deposit (40 cm of rootlet and fen peat). Below this contact, there is an organic-rich gyttja deposit (37–40% C) down to 65-cm depth. The underlying gyttja deposits suggest that peat formation could have been initiated following terrestrialisation of a small pond or thermokarst lake. The oldest peat deposit underlying fen vegetation started accumulating around 3925 cal yrs BP (54 cm of peat at site TL 2-6). There are gyttja deposits underlying this dated peat horizon, suggesting that the nearby small lake once covered this site. The bog peat deposit at nearby TL 2-7 is deeper, but has a similar age of 3735 cal yrs BP. As the peat deposits in the raised bog peatlands consist almost entirely of fen peat, we assume that these belonged to the same fen complex. The other two ^{14}C-dated fen peatlands have young basal ages around ~1000 cal yrs BP (TL 3-5 and TL 3-6). These two sites are located only 100 m apart in a fen complex following the margin of a lake. The dated organic deposits in these fens are mainly gyttja with thin (<10 cm) layers of overlying peat, indicating relatively recent terrestrialisation at these sites. The dated basal samples from surface O-horizons (32–35 cm) in soils of wet shrub tundra sites are between 3500–4000 cal yrs BP, pointing to long residence times of SOM in these poorly drained soils.

There is no correlation between basal age and the depth of peat deposits. Possible causes for this are: (i) large variations in peat accumulation rates over time and in different peatland plant assemblages (Sannel and Kuhry, 2009), (ii) spatial variability in ground-ice content, or (iii) surface abrasion decreasing the depth of some deposits (Seppälä, 2003), as indicated by the lack of rootlet peat layers on the surface of younger bog peat deposits (only TL 2-2, the oldest deposit, has a rootlet peat surface layer).

Upscaling and Mean Storage of SOC

The estimated mean C 0–100 cm storage in the LCC study area is 33.8 $kg\,C\,m^{-2}$, while the transect-based upscaling yields an estimate of 37.1 $kg\,C\,m^{-2}$. The main difference between the two upscaling methods arises from differences in bog peatland coverage: 16 per cent of the LCC study area and 21 per cent of the transects are classified as bog. The validity of upscaled SOC estimates is highly dependent on the thematic accuracy of the upscaling proxies. Many of the

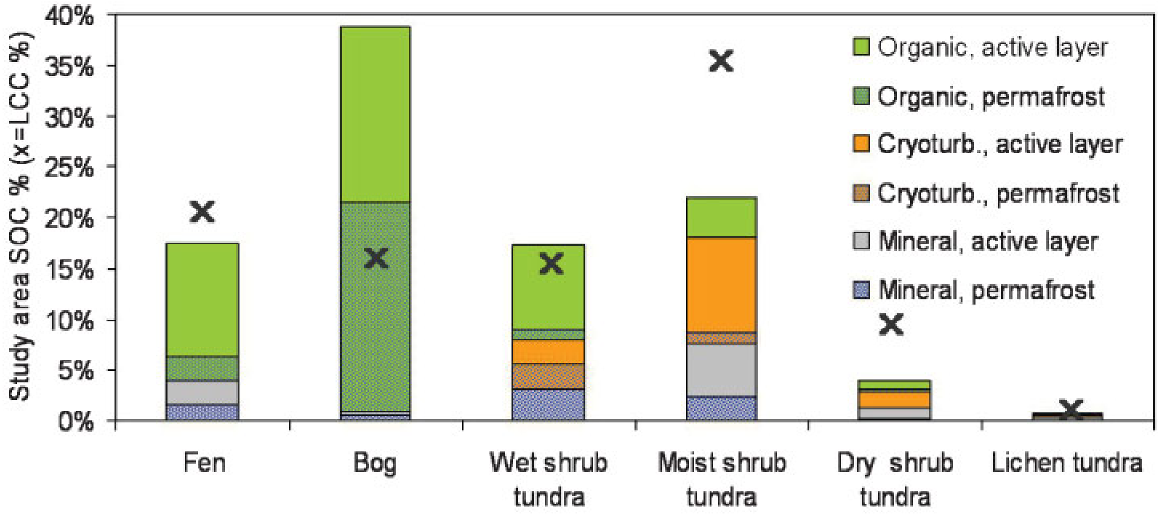

Figure 5 Graph shows percentage of total SOC storage divided by land cover types. Subdivision shows partitioning between top organic layers, cryoturbated pockets and mineral subsoil with active-layer storage separated from permafrost storage. Crosses show percentage land cover in the study area (lakes excluded from the calculation). The terms active layer and permafrost refer to the position of the frost table at the time of sampling (real active-layer storage will likely be somewhat higher). Abbreviations are defined in the text.

vegetation types we classified form a continuum, and objective classification of these classes can be difficult (even *in situ*). The thematic accuracy of the transect inventory is not tested but it should be very high as it is based on field descriptions. The satellite LCC has a kappa index of agreement value of 0.71, which shows good thematic accuracy of the classification. When compared to the LCC, limited spatial coverage of the transect inventories is the obvious disadvantage, and in this study the transect method overestimates the coverage of bogs and underestimates moist and dry tundra classes (Table 1).

There are also some difficulties with landscape upscaling and the use of remotely sensed data. Tundra vegetation is difficult to map with discrete thematic classes in $30 * 30$-m pixels when vegetation types often vary at a finer scale. As a result of the above-mentioned issues and edge effects such as mixed pixels, the LCC is not expected to be correct at every point, but over larger areas it provides a realistic estimate of land cover.

In the *Soil Organic Carbon of Canada*, map (Tarnocai and Lacelle, 1996), SOC storage in the study area is estimated to be between 14 and 24 $kg\,C\,m^{-2}$. Our new landscape estimate of 33.8 $kg\,C\,m^{-2}$ is considerably higher. A better representation of peatlands in our high-resolution upscaling tool is the main reason for the large increase between the current estimate and the corresponding polygons in the *Soil Organic Carbon of Canada*, map. The *Soil Organic Carbon of Canada*, map is a regional-scale product based on the *Soil Landscapes of Canada* database (Centre for Land and Biological Resources Research, 1996, produced for 1:1 000 000 scale). In this database, the organic soil fraction for the two polygons overlapping the LCC region is 0 per cent (71% and 61% classified as Orthic Turbic Cryosolic, the rest as acidic hardrock). Likewise, a low-resolution, continent-scale land cover dataset (GLC 2000, Latifovic *et al*., 2002) has no wetland pixels within these polygons.

Ping *et al*. (2008) estimated mean SOC storage within the lowlands of the North American Arctic region based on 139 pedons upscaled using the Circumpolar Arctic Vegetation Map (Walker *et al*., 2005). The Tulemalu Lake study area is located within bioclimatic subzone E (low shrub or Low Arctic zone) for which SOC 0–100-cm storage is estimated to be approximately 45 $kg\,C\,m^{-2}$, with approximately 19 $kg\,C\,m^{-2}$ occurring in permafrost. Although the Ping *et al*. (2008) estimate for subzone E relates to the North American Low Arctic region, the soil database for the Low Arctic mainly contains pedons from the Seward Peninsula of Alaska with some data from the boreal forest region of Canada, but contains no pedons from the central Canadian Low Arctic. Using Alaskan Low Arctic pedons and Canadian boreal pedons to estimate SOC storage in the central Canadian Low Arctic may have led to an overestimation of SOC pools.

Partitioning of SOC, Peatlands and Cryoturbation

Peatlands occupy 37 per cent of the study area and contain 56 per cent of the SOC mass. The PCA illustrates the interconnected gradients in depth of organic deposits, permafrost and SOC storage. Bogs have thick insulating peat deposits storing 39 per cent of the total SOC pool and 59 per cent of the permafrost SOC pool (within 16% of the total area). Hugelius and Kuhry (2009) found more pronounced peatland dominance of SOC storage in the (forest-)tundra of NE European Russia (discontinuous to continuous permafrost). There, bog peatlands hold 60 per cent of the total SOC pool and 99 per cent of the perennially frozen SOC pool.

In the Tulemalu study area, fen vegetation covers larger areas than bogs but the underlying peat and gyttja deposits are thin and store relatively little SOC (17% of the total SOC pool, 21% of the area). It is possible that our sample of fen sites is biased towards underestimation of SOC storage. Six out of seven sampled fens have low mean SOC storage with relatively thin surface organic layers. These fens all belong to the same fen peatland complex with young basal ages in gyttja suggesting recent terrestrialisation, a situation that may not be representative for the fens in the larger surrounding region.

The PCA diagram shows that shrub tundra sites have a higher variability in SOC partitioning than do lichen tundra or peatland classes. These differences are due to variability in the thickness of surface organic layers and burial of SOM through cryoturbation. Wet shrub tundra sites especially have accumulated thick surface organic horizons (with high basal ages), but they also store a lot of SOC in cryoturbated soil pockets. The thickness of surface organic layers in tundra vegetation follows a moisture gradient, showing that it is important to make a distinction between tundra land cover classes. While the choice of land cover classes accounts for the variability in thickness of surface organic horizons, our upscaling scheme does not account for the spatial variability of cryoturbation processes (beyond the statistical advantages of a stratified random-sampling approach).

Low MAAT and frequent freeze-thaw cycles are important climatic controls of cryoturbation, but local-scale conditions such as poor drainage or silt/loam-rich soil parent material are also known to favour the process (Washburn, 1980). In a study of Northern Alaskan soils, Bockheim (2007) found that patterned ground formation (ice wedges and frost boils), soil silt content and poor drainage are key environmental factors regulating the storage of SOC in cryoturbated soil horizons. In the Tulemalu Lake study area, cryoturbation processes are only active in soils developed on loamy till parent material (Turbic Cryosols found in all catenary positions). Soils developed on sandy deposits are non-cryoturbated.

In Turbic Cryosols, C/N ratios of SOM in cryoturbated soil pockets and surface O-horizons are similar, but significantly higher than C/N ratios of SOM in non-cryoturbated mineral horizons. Although radiocarbon dating suggests that deeper cryoturbated SOM is older than surface SOM (Table 2), the C/N ratios indicate a similar degree of decomposition. In a study of Siberian Turbic Cryosols, Kaiser *et al*. (2007) showed that cryoturbation of A-horizons deeper into the active layer retarded decomposition of SOM.

Cryoturbated pockets in Turbic Cryosols hold 17 per cent of the total landscape SOC mass, four-fifths of which is stored in the active layer. On average, 51 per cent of the SOC mass in Turbic Cryosols is stored in cryoturbated soil pockets. This is similar to results from Bockheim (2007) who found that 55 per cent of SOC in the top metre of Alaskan Turbels (Turbic Cryosols) is stored in cryoturbated soil genetic horizons.

Recent studies have demonstrated the importance of SOC storage in deeper (>1 m), mostly perennially frozen, cryoturbated horizons (Bockheim and Hinkel, 2007; Schuur *et al*., 2008). Tarnocai *et al*. (2009) estimate that in cryoturbated soils, 38 per cent of the SOC mass is stored in the top metre, 33 per cent in the second metre and 28 per cent in the third metre. Using this approach, mean SOC storage in Turbic Cryosols in our study area increases to 67.6 kg C m^{-2}, of which 43.2 kg C m^{-2} is stored in permafrost. If we apply this correction to all cryoturbated sites in our data, also adding a default for 30 cm of mineral soils underlying deep peat deposits (based on mineral horizons underlying peat in our dataset), mean SOC storage in the study area as a whole increases to 52.9 kg C m^{-2}.

CONCLUSIONS

The SOC 0–100 cm estimate for the Tulemalu Lake study area is 33.8 kg C m^{-2} (a third of which is perennially frozen). This is higher than previous estimates for this part in the central Canadian Arctic (14–24 kg C m^{-2}), mainly because high-resolution, local-scale upscaling provides more realistic peatland coverage. Two-thirds of the SOC is stored in surface organic soil horizons, mainly in bog peatlands. These peat deposits started to accumulate in fens during the Middle Holocene (~6000 cal yrs BP) in a forest-tundra environment with continuous permafrost. Cryoturbation processes have been occurring in the study area at least since the Middle Holocene, and Turbic Cryosols store 17 per cent of the total 0–100-cm landscape SOC 0–100 cm storage pool in cryoturbated soil pockets. Bulk elemental C/N ratios indicate that this cryoturbated SOM decomposes more slowly than SOM in surface O-horizons. However, the present land cover upscaling proxy does not sufficiently account for the spatial distribution patterns of cryoturbation and there is a need to further develop upscaling tools. A recalculation of our data applying recently published default corrections for SOC storage in deeper cryoturbated soil horizons (1–3 m) further highlights the importance of including these deposits in future field studies, despite considerable logistical constraints.

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APPENDIX 1

Appendix 1 Properties of investigated soil pits. Table shows soil classification according to the WRB and Canadian soil classification systems, the parent material (including texture), presence of cryoturbation in the soil profile, depth of thaw at sampling and depth of top organic deposits, the drainage conditions at the site, presence of patterned ground and land cover.

Pedon name	Soil Classification		Parent material (texture)	Cryoturb.	Organic layer (cm)	Thaw depth (cm)	Drainage[b]	Patterned ground[c]	Land cover/ Remarks
	WRB	Canadian[a]							
TL1-1	Haplic Cryosol	RSC	Raised shore (sand)	no	2	89	W	IWP	Lichen tundra
TL1-3	Histic Turbic Cryosol	HDTC	Till (sandy loam)	yes	27	34	VP	None	Wet shrub tundra
TL1-8	Histic Leptic Turbic Cryosol	HDTC	Peat over rock	yes[d]	26	>38	P	None	Wet shrub tundra
TL1-11A	Turbic Cryosol	HDTC	Till (sandy loam)	yes	20	79	I	NSC	Moist shrub tundra
TL1-11B	Turbic Cryosol	ODTC	Till (sandy loam)	yes	5	100	W	NSC	Dry shrub tundra
TL2-2	Cryic Hemic Histosol	HRSC	Peat over sand	no	42	33	MW	IWPP	Bog peatland
TL2-4	Turbic Cryosol	ODTC	Till (sandy loam)	yes	5	95	MW	NSC	Moist shrub tundra
TL2-6	Cryic Histosol	TMOC	Peat over sand	no	40	40	P	None	Fen peatland
TL2-7A	Cryic Hemic Histosol	MOC	Peat over sand	no	105	33	MW	IWPP	Bog peatland
TL2-7B	Cryic Hemic Histosol	MOC	Peat over sand	no	113[e]	33	MW	IWPP	Eroding bog peat bank
TL2-11	Turbic Cryosol	ODTC	Till (sandy loam)	yes	8	40	I	NSC	Moist shrub tundra
TL3-1	Turbic Cryosol	ODTC	Till (sandy loam)	yes	14	106	P	NSC	Wet shrub tundra
TL3-4	Cambic Cryosol	BDSC	Glaciofluvial (sand)	no	4	95	R	None	Lichen tundra
TL3-9	Histic Cryosol	HRSC	Glaciofluvial (sand)	no	30	53	P	None	Gyttja fen over sand
TL3-10	Histic Cryosol	HRSC	Glaciofluvial (sand)	no	25	75	P	None	Gyttja fen over sand
TL3-11	Cryic Hemic Histosol	MOC	Peat over rock	no	100	34	M	IWPP	Bog peatland

[a] Soil classification (Canada): ODTC: Orthic Dystric Turbic Cryosol; HDTC: Histic Dystric Turbic Cryosol; RSC: Regosolic Static Cryosol; HRSC: Histic Regosolic Static Cryosol; BDSC: Brunisolic Dystric Static Cryosol; MOC: Mesic Organic Cryosol; TMOC: Terric Mesic Organic Cryosol

[b] Drainage: R: rapid; W: well; MW: moderately well; I: imperfect; P: poor; VP: very poor

[c] Patterned ground: IWP: large ice-wedge polygon; IWPP: ice-wedge peat polygon; NSC: non-sorted circle

[d] Frost-heaved stones

[e] Measured at a site where eroded peat blocks overlie undisturbed peat