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Storage, landscape distribution, and burial history of soil organic matter in contrasting areas of continuous permafrost

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Abstract

This study describes and compares soil organic matter (SOM) quantity and characteristics in two areas of continuous permafrost, a mountainous region in NE Greenland (Zackenberg study site) and a lowland region in NE Siberia (Cherskiy and Shalaurovo study sites). Our assessments are based on stratified-random landscape-level inventories of soil profiles down to 1 m depth, with physico-chemical, elemental, and radiocarbon-dating analyses. The estimated mean soil organic carbon (SOC) storage in the upper meter of soils in the NE Greenland site is 8.3 ± 1.8 kg C m^{-2} compared to 20.3 ± 2.2 kg C $m^{-2}$and 30.0 ± 2.0 kg C m^{-2} in the NE Siberian sites (95% confidence intervals). The lower SOC storage in the High Arctic site in NE Greenland can be largely explained by the fact that 59% of the study area is located at higher elevation with mostly barren ground and thus very low SOC contents. In addition, SOC-rich fens and bogs occupy a much smaller proportion of the landscape in NE Greenland (~3%) than in NE Siberia (~20%). The contribution of deeper buried C-enriched material in the mineral soil horizons to the total SOC storage is lower in the NE Greenland site (~13%) compared to the NE Siberian sites (~24%–30%). Buried SOM seems generally more decomposed in NE Greenland than in NE Siberia, which we relate to different burial mechanisms prevailing in these regions.

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Introduction

Estimates indicate that soils in the northern circumpolar permafrost region, which occupy an area of about 18.8 million km^2 (or ~16% of the global soil area), hold a belowground soil organic carbon (SOC) pool of ~1672 Pg C (Tarnocai et al., 2009). These soils are vulnerable to permafrost degradation under global warming and, if they thaw, soil organic matter (SOM) decomposition could release large amounts of carbon dioxide (CO_2) and/or methane (CH_4) into the atmosphere, providing a positive feedback to climate warming (Schuur et al., 2008). During recent decades, permafrost has already shown a strong warming trend and, furthermore, the most pronounced future climate warming is expected to take place in the high latitude northern continental regions (Vaughan et al., 2013).

Tarnocai et al. (2009) highlighted that large uncertainties remain in the SOC estimates for the northern permafrost region, including the High Arctic and Eurasian sectors. Therefore, more empirical evidence from these sectors is essential to improve estimates. The objective of this study is to describe the SOM quantity and characteristics in two areas of continuous permafrost, the High Arctic of NE Greenland (Zackenberg study site) and the taiga-tundra ecotone in NE Siberia (Cherskiy and Shalaurovo study sites). Previous studies from these areas present C storage estimates calculated on samples that were taken mostly in the active layer (Elberling et al., 2008; Mergelov and Targulian, 2011). This study represents a considerable improvement, as it includes frozen soil to a depth of 1 m. SOC contents from individual pedons are upscaled using land cover and transect based upscaling to estimate the SOC pools at a landscape scale. Studies of similar detail are only available for a few other regions in the continuous permafrost zone, for example, the Kuparuk Basin in N Alaska (Michaelson et al., 1996), the Tulemalu Lake area in central Nunavut (Hugelius et al., 2010), and the Lena Delta in N Siberia (Zubrzycki et al., 2013). Our assessments for degree of decomposition and burial history of SOM are based on carbon to nitrogen ratio (C/N) analyses and radiocarbon dates. The overall goal of this study is to provide high quality data from undersampled regions for a future assessment of the potential remobilization of SOC under global warming, taking into account total storage, landscape and soil horizon partitioning, and degree of decomposition of SOM in permafrost terrain.

Study Areas

We investigated two high-latitude northern regions within the continuous permafrost zone (Brown et al., 1997). The first study site corresponds to the area surrounding the Zackenberg Research Station in

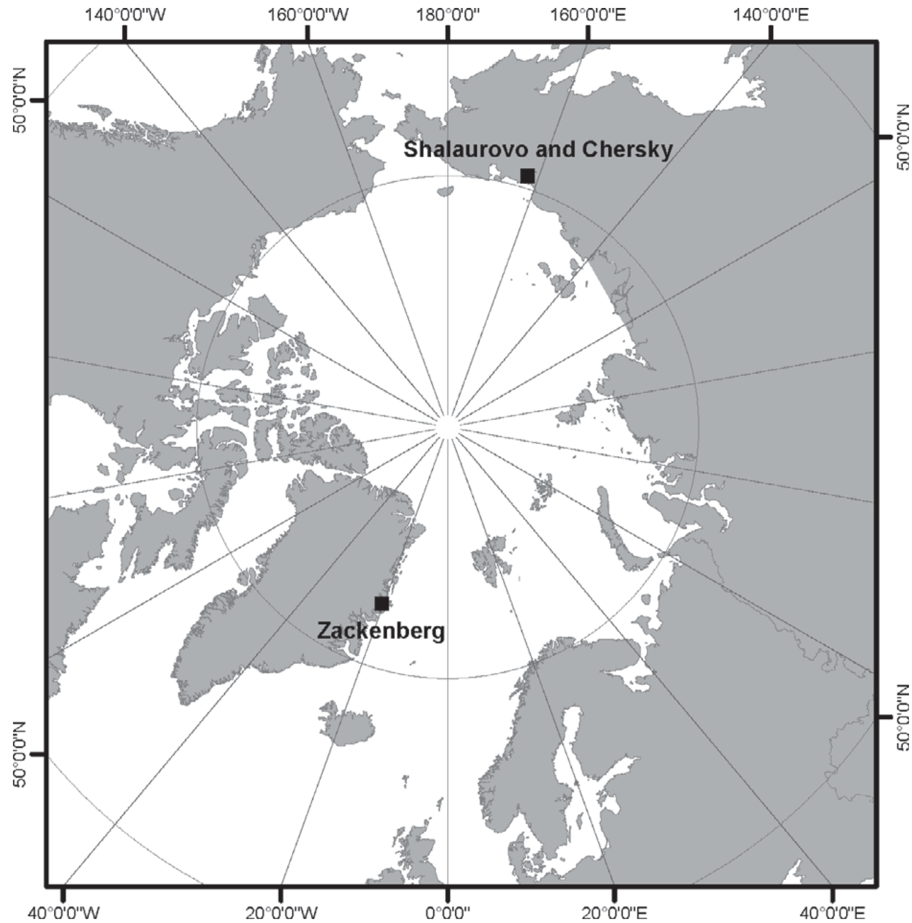

FIGURE 1. Location of the Zackenberg study site in NE Greenland, and the Cherskiy and Shalaurovo study sites in NE Siberia.

NE Greenland (74°28′N, 20°34′W, Fig. 1). The landscape is mountainous with a broad, flat central valley. The altitudinal range extends from sea level to the top of Zackenberg Mountain (0–1372 m). The Zackenberg valley was created by a large fault system, dividing the Caledonian gneiss/granite bedrock, which is exposed in the mountains in the west, from the Cretaceous-Tertiary sedimentary rocks, exposed in the east (Escher and Watt, 1976). The deglaciation of the central valley occurred prior to 11,300 calibrated years before the present (cal yr B.P.) (Bennike et al., 2008). The parent material in the lower Zackenberg valley is mostly derived from glaciofluvial, deltaic, eolian, and, locally, moraine deposits. On slopes and at higher elevations, solifluction materials and boulder fields are dominant (Christiansen et al., 2008).

The regional climate in Zackenberg is high-arctic with a mean annual temperature in the central valley of –9.2 °C; the mean annual precipitation is about 200 mm of which 10% falls as rain during the summer months from June to September (Hansen et al., 2008). At least five major plant communities can be identified in the Zackenberg valley (Elberling et al., 2008). Areas that are saturated by water during the whole growing season are dominated by fens (*Dupontia psilosantha, Eriophorum scheuchzeri*). Areas with gentle slopes and changing water regimes throughout the growing season, from wet during the snow melt to moist by the end of the summer, are dominated by grasslands (*Arctagrostis latifolia, Eriophorum triste, Alopecurus alpina*). Drier microhabitats in the central valley are dominated by heath vegetation (*Cassiope tetragona*). Patches on slopes that are characterized by long-persisting snow cover are the so-called snowbeds (*Salix arctica* dominant, with *Stellaria crassipes, Luzula confusa, Luzula arctica, Poa arctica*). On dry and wind-exposed places, often at higher elevations, scarce heath is characteristic (*Dryas octopetala* dominant, with *Kobresia myosuroides, Carex rupestris, Poa glauca*). Above 200–400 m elevation, vegetation becomes very sparse or is completely absent. These areas are classified as patchy boulder fields, boulder fields, fell fields, abrasion plateaus, and barrens.

The field sites of the second study region are located in the taiga and tundra biomes of the Kolyma Lowlands in NE Siberia (Fig. 1), which are limited in the North by the East Siberian Sea and bordered in the south by the foothills of the Kolymskiy Range. The whole area was mostly unglaciated during the Pleistocene (Brubaker et al., 2005). The dominant soil material of the Kolyma Lowlands is Late Pleistocene syngenetic deposits (Yedoma Ice Complex), mostly polygenetic silty sediments with large occurrences of massive ice wedges (Schirrmeister et al., 2011).

The climate in the Kolyma region is continental. In the taiga field sites near the town of Cherskiy (68°45′N, 161°29′E), the mean annual temperature is –11.3 °C with a high amplitude between mean July and mean January temperatures (~50 °C). The average annual precipitation is about 290 mm, 50% of which occurs during the summer months. The forests around the town of Cherskiy are located near the northern limit of the taiga and are dominated by *Larix gmelinii*. The Shalaurovo field site (69°27′N, 161°48′E) is located in the southern tundra, ~80 km to the north of Cherskiy. Lashchinskiy (2013) described well-drained upland vegetation dominated by shrubby tussock moss tundra (*Eriophorum vaginatum, Tomenthypnum nitens, Aulacomnium palustre*), while areas with gentle slopes are vegetated mainly by shrubby grass tundra (*Arctagrostis latifolia, Bistorta elliptica, Aconogonon tripterocarpum*). Steep northern slopes are characterized by *Equisetum* communities, whereas creeks and depressions are dominated by willow moss communities (*Salix pulchra, Aulacomnium palustre*) and sedge moss fens (*Carex stans, Sphagnum squarrosum*).

Methods

FIELD SAMPLING

Soil profiles were sampled during late summer (NE Greenland 2009, 2012; NE Siberia 2010) when the maximum seasonal thaw (active layer) depth is reached. The aim of the sampling campaigns was to capture all important land cover classes and landforms within the study sites. The sampling was based on straight transects across the landscape, which were established after initial detailed field reconnaissance. Once the first point of each transect was defined, the following ones were positioned equidistantly using a global positioning system (GPS). This approach introduces a degree of randomness in the collection of soil profiles. The distance between sampling points could vary among transects, depending on geomorphological setting and landscape patterns.

At all study sites, samples in permafrost were collected using a steel pipe that was hammered into the soil at 5 to 10 cm depth increments until at least 100 cm of depth (where possible). The sampling in NE Siberia differed from NE Greenland in that, if possible (e.g., at dry sites), soil pits were excavated down to the permafrost, and the active layer was sampled using a fixed volume cylinder inserted horizontally into the exposed pit (generally at 10 cm intervals). In NE Siberia, unfrozen fen deposits were sampled using a Russian peat corer. Profiles in NE Greenland are entirely collected by steel pipe, except for the top organic layer. The top organic layer thickness can vary substantially even at fine spatial scales. Therefore, three randomly selected replicates were collected at all sites (excluding peatlands) in both NE Siberia and NE Greenland in order to get more representative estimates for this soil horizon. Each site was described and documented in detail concerning permafrost depth (if reached), water table depth (if reached), topographic/catenary position (including slope and aspect), occurrence of stones on the soil surface and in the soil profile, land cover, and soil type (classified following the U.S. Department of Agriculture Soil Taxonomy).

SOIL CHEMICAL ANALYSES AND RADIOCARBON DATING

All soil samples ($n = 887$) from 72 collected soil profiles were weighed after being oven-dried at 70 °C for at least 24 hours to calculate dry bulk density (BD, g cm^{-3}). Loss on ignition (LOI) was used to determine organic matter and inorganic carbonate content (Dean, 1974; Heiri et al., 2001). Each dried sample was first homogenized and then burned at 550 °C for 5 hours to calculate the weight percentage loss of organic matter (LOI550, %). Subsequently, at least three randomly chosen samples from each profile representing different soil horizons ($n = 264$) were burned at 950 °C for another 2 hours to establish the weight percentage loss of carbonate (LOI950, %).

To determine the elemental content of carbon (C) and nitrogen (N), samples were run through an EA 1110 Elemental Analyzer (CE Instruments). In total, 788 samples including 67 duplicates were analyzed, 323 samples from NE Greenland (fieldwork 2009) and 465 samples from NE Siberia. The 87 soil samples from NE Greenland collected during fieldwork in 2012 were not included in the elemental analyses, but LOI data are available for these samples. The organic C content for these samples was estimated using a third-order polynomial regression between the LOI550 (x) and %C (y) based on the 2009 NE Greenland samples for which both analyses are available ($n = 284$, $y = -0.000028x^3 + 0.003193x^2 + 0.398851x$; $R^2 = 0.97$).

The relationship between C and N is expressed as C/N weight ratios. The independent t-test was used to evaluate if the mean of C/N ratios from the different types of sampled material (top organic or peat layer, buried organics, and mineral horizons) are statistically different from each other.

Altogether, 46 bulk samples were submitted for accelerator mass spectrometry (AMS) ^{14}C dating to the Poznan Radiocarbon Laboratory, Poland. Radiocarbon ages (expressed in cal yr B.P.) were calibrated using Oxcal 4.2 (Bronk Ramsey, 2010). Pearson's r correlation analyses were performed to investigate relationships between soil organic matter age vs. depth and SOC vs. N 0–100 pools. All statistical tests were performed in the software IBM SPSS Statistics for Windows, version 21.0, and were considered significant if $p < 0.05$.

SOIL ORGANIC CARBON CALCULATIONS

Soil organic carbon (SOC) content was calculated for each analyzed sample using the following equation:

$$SOC(g\ C\ cm^{-3}) = BD\ x\ \%C\ x\ (1 - CF) \quad (1)$$

where *BD* is the dry bulk density of the sample (g cm^{-3}), *%C* the percent organic C in the sample (%), and (1 – *CF*) the remaining proportion of the sample after excluding the coarse mineral fractions (>2 mm). Many of the profiles in NE Greenland were rich in coarse fragments and, often, stones or rocks were encountered before reaching 1 m depth. No correction for coarse fragments was necessary in the NE Siberian study sites as these were never encountered during sampling. Values for some missing samples were interpolated by means of the SOC contents in the samples directly above and below whereby the presence of ice and buried organic layers based on the field descriptions were taken into account.

Total SOC storage (kg C m^{-2}) in each soil profile, calculated for the standard 0–30 cm and 0–100 cm depth intervals, the top organic/peat layer, mineral subsoil layer, active layer, permafrost layer, and buried organic layers, is obtained by multiplying the SOC content of each sample by the depth interval it represents, multiplying by a factor of 10 (unit conversion), and adding up those values corresponding to the different soil horizons of interest. Because the top organic layers vary greatly in thickness and storage, their SOC values were calculated as the mean from the three collected replicates (Hugelius et al., 2010).

In this study, the main purpose of analyzing the nitrogen (N) content of soil samples was to calculate C/N weight ratios. However, this data also allows calculation of total soil N stocks as described for SOC.

LANDSCAPE CLASSIFICATION AND UPSCALING METHODS

A land cover classification for the Zackenberg study site in NE Greenland was already available (Elberling et al., 2008). The land cover map has a spatial resolution of 5 m resampled to 10 m × 10 m. It provides the distribution and total extent of the main land cover classes at Zackenberg, which in turn were used to describe the land cover at the collected soil profiles. The maximum-likelihood classification was carried out in ENVI 4.2 and based on an aerial hyperspectral HyMap campaign from 8 August 2000 and ground-truthing in the field during

July 2005. The land cover classification for the Shalaurovo study site in NE Siberia is based on QuickBird imagery with a multispectral resolution of 2.4 m (acquired 2 July 2011). The image classification was performed in ENVI 4.8 using supervised maximum-likelihood classification. To verify its accuracy, 52 independent ground-truthing points (plot size 10 m × 10 m), subdivided into seven vegetation classes were used. The classification was considered correct when the land cover classification pixel and the ground-truthing point showed identical land cover. The same classes were utilized to describe the land cover at the collected soil profiles. No land cover products are available for the Cherskiy study site in NE Siberia.

The areal coverage for the Zackenberg study site is 11.5 km × 12.0 km (138 km^2), of which 17.8 km^2 (12.9%) is occupied by seawater (Young Sound–Tyrolerfjord). In Shalaurovo, the land cover classification has an aerial coverage of 9.8 km × 12.0 km (118 km^2) with 33 km^2 (28%) occupied by the Kolyma River. These larger areas of seawater and river water were excluded and therefore the calculations refer to terrestrial SOC storage only (but including lakes and small riverbeds). Even though the established field transects for soil sampling are not spread out over the entire areas of the Zackenberg and Shalaurovo land cover classification maps, the areas were fully explored in the field to confirm that all land cover classes in the larger areas are similar to those observed along the transects. In both study areas, lakes and riverbeds are considered as their own land cover class and are included in the mean SOC estimates. While these classes were sampled in Zackenberg, in Shalaurovo values for lakes and riverbeds are taken from other studies. In Zackenberg, areas of mountain shadow, cloud shadow, and high-elevation late seasonal snow cover are reinterpreted in terms of likely land cover classes based on their landscape position.

To calculate the mean SOC storage for each land cover class and their different soil horizons, we use the arithmetic mean from the sampled profiles within the same land cover class. The landscape-level mean SOC storage (for each of the recognized soil horizons) at each study site is calculated by multiplying the mean SOC storage of each class by its proportional representation in the land cover classification and adding up these values for all represented land cover classes. In the case of the study sites at Cherskiy, the upscaling is based upon the proportional representation of land cover classes along the sampled transects. Estimates of mean soil N storage for each land cover class and the landscape level at each study site is provided for the 0–100 cm soil depth interval only.

Quantitative 95% confidence intervals (CI) for landscape SOC and N stock estimates, weighed for the variance within and areal coverage of each upscaling class *i*, were calculated using the following equation:

$$CI = t\ x \sqrt{\left\{\sum\left[\left(ai^2 x\ StDi^2\right) / ni\right]\right\}} \qquad (2)$$

where *t* is the upper $\alpha/2$ of a normal distribution ($t \approx 1.96$), *ai* = total area % of the class *i*, *StDi* = standard deviation of the class *i*, *ni* = number of replicates in class *i* (Thompson, 1992).

Results

SOIL TYPES, ACTIVE LAYER DEPTH, AND BURIED ORGANICS IN NE GREENLAND AND NE SIBERIA

A total of 38 soil profiles along six different transects were sampled in the Zackenberg study site (Fig. 2). The predominant soil type in mineral ground of the central valley is a weakly developed Typic Psammoturbel, whereas on slopes it is Gelorthents. In peaty soils, fens are classified as Hemistels or Histoturbels depending on the thickness of the organic layer. Highly localized permafrost raised bog features (palsas and pounus) within the fens are classified as Folistels (Soil Survey Staff, 2010).

Permafrost was reached in 9 out of 10 peat profiles (Table 1), with an average active layer thickness in bogs of 34 cm (n = 2) and in fens of 55 cm (n = 7). Two shallow wetland ponds had a mean active layer of 80 cm. In the mineral soils, permafrost was reached in 9 out of 24 profiles. The average active layer depth at these sites was 77 cm. It was not possible to reach permafrost in 11 shallow profiles because of the occurrence of rocks and stones. In a few other cases, coring could be continued until 1 m without encountering the upper permafrost table (n = 4). Two deeper lakes in morainic landscape had no permafrost in their sediment sequences (Bennike et al., 2008).

Buried soil organic material was found in 11 out of 38 sites (Table 1), mostly confined to the wet profiles of fens (n = 7 out of 8) but also in a few moist profiles in grasslands (n = 3 out of 6). We found no buried organics below the peat deposits in bogs and in dry upland soil sites, with the exception of one fell field site. In addition, Elberling et al. (2008) reports cryoturbated C-enriched material in the active layer of a *Cassiope* heath site.

The prevailing mineral soil types in the taiga and tundra study sites of NE Siberia are Histoturbels. Haploturbels are dominant on floodplains. In peat soils, the characteristic soil type is Folistel in raised peat bogs and Hemistel in fens (Soil Survey Staff, 2010). Our soil survey in Shalaurovo consists of two transects with 20 profiles (Fig. 3). The permafrost table was reached in each profile and the mean active layer thickness during the sampling period in August 2010 was 56 cm in the organic soils and 62 cm in the mineral soils (Table 2). The riverbed and lake sites included in our database but derived from other studies have reported upper permafrost tables at depths of >100 cm. Signs of cryoturbation were found in 15 out of 20 sites. Cryoturbated organics are found in both the active layer and upper permafrost layer. About 80% of the mineral upland soils display C-enrichment at the upper permafrost table.

A total of 14 profiles along three transects were collected near the town of Cherskiy, including forest-peatland transitions in the lowlands, the forest-alpine tundra transition on a nearby hill, and the forest-tundra transition ~25 km north of town. The active layer thickness is on average slightly shallower in Cherskiy than in Shalaurovo, with 47 cm in peat soils and 58 cm in mineral soils (Table 3). The taiga sites were in general less cryoturbated; 7 out of 14 profiles showed signs of cryoturbation (Table 3). As in Mergelov and Targulian (2011), about half of the mineral upland soils display C-enrichment at the upper permafrost table.

SOC STORAGE AND LANDSCAPE UPSCALING IN NE GREENLAND

An assessment of the land cover classification for the Zackenberg study site (Fig. 2), performed with independent ground-truthing, shows an overall accuracy of 72%. However, main vegetation types (e.g., *Cassiope* heath, fens, and grasslands) had classification accuracies above 80%. The mean SOC storage for each of the land cover classes and their different soil horizons as well as the weighed average for the whole land area are presented in Table 1.

Some higher elevation land cover classes such as barrens (occupying ~10% of the total area), snow (~5 %), and abrasion plateau (<1%) were not sampled. Field observations indicate that barrens are devoid of any vegetation and soil formation (we consider the SOC content negligible). The land cover class

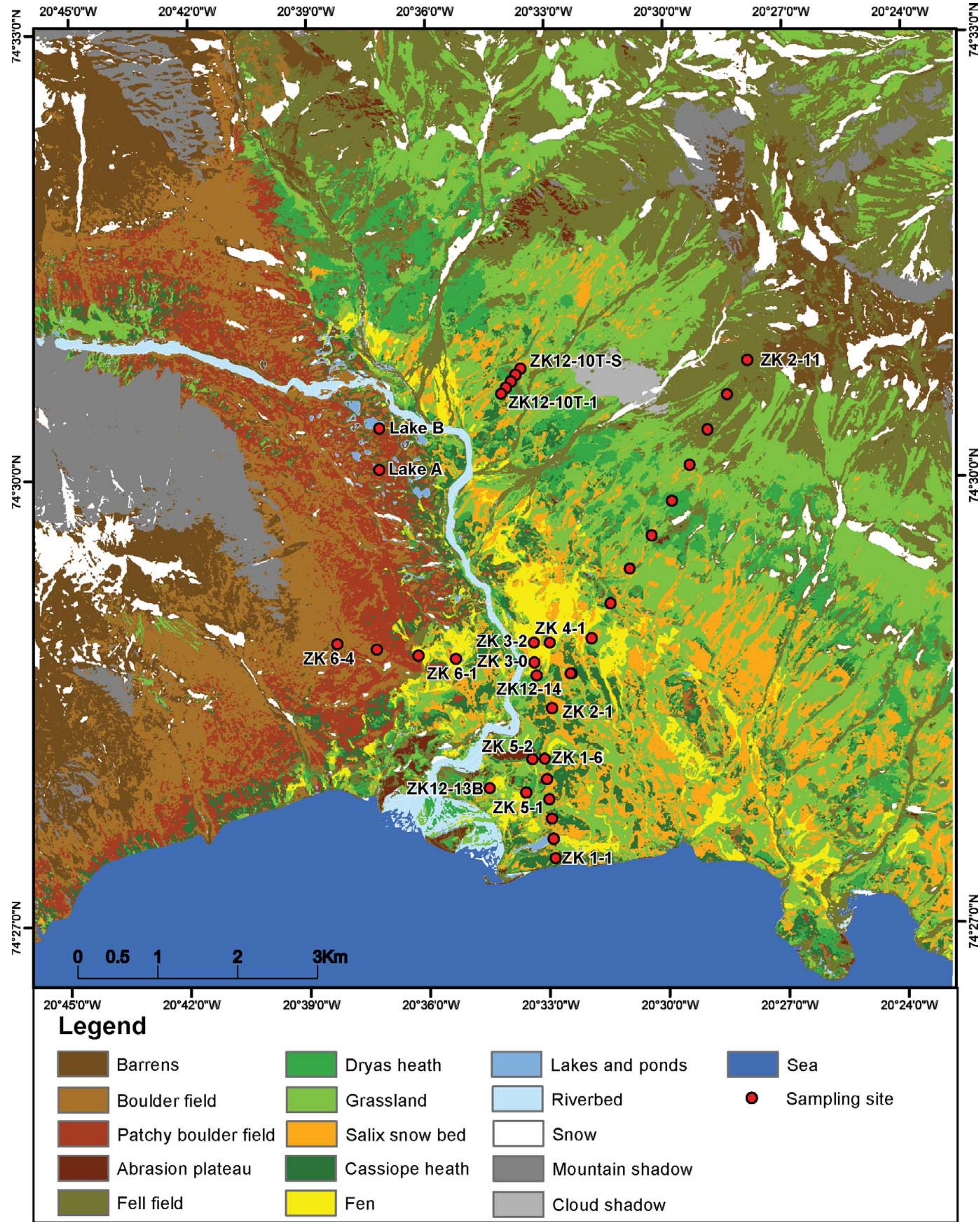

FIGURE 2. **Distribution of land cover classes and location of transects and profile sites in Zackenberg, NE Greenland. Lake A and Lake B sites after Bennike et al. (2008) and B. Elberling (personal communication). Land cover classification after Elberling et al. (2008). Coordinate system UTM Zone 27N. [this figure will cost $150 to publish.]**

TABLE 1

Mean SOC storage estimates (kg C m^{-2}) and total N for the Zackenberg study site (NE Greenland), by land cover classes and soil horizons.

Land cover class	Proportion of total area (%)	*n*	Mean ± SD depth organic layer (cm)	Mean ± SD depth active layer [a] (cm)	Mean ± SD SOC 0-30 cm (kg C m^{-2})	Mean ± SD SOC 0-100 cm (kg C m^{-2})	Mean ± SD N 0-100 cm (kg N m^{-2})	Mean ± SD Organic layer (kg C m^{-2})	Mean ± SD Mineral layer (kg C m^{-2})	Mean ± SD Active layer (kg C m^{-2})	Mean ± SD Permafrost layer (kg C m^{-2})	Mean ± SD Buried organics in active layer [b] (kg C m^{-2})	Mean ± SD Buried organics in permafrost [b] (kg C m^{-2})
Boulder field	10.0	1	0.2	?	1.32	3.65	0.5	0.06	3.59	3.65	0	0	0
Patchy boulder field	6.2	3	7.3 ± 4.2	?	0.6 ± 0.4	2.0 ± 1.4	0.1 ± 0.0	0.3 ± 0.3	1.7 ± 1.1	2.0 ± 1.4	0	0	0
Fell field	19.9	5	0.9 ± 0.7	> 100 (*n*=1)	1.0 ± 0.8	2.4 ± 1.7	0.2 ± 0.1	0.1 ± 0.1	2.3 ± 1.7	2.5 ± 1.7	0	1.1 (*n*=1)	0
Cassiope heath	3.8	3	5.0 ± 0.6	82, > 100 (*n*=2)	3.9 ± 1.5	10.5± 5.6	0.8 ± 0.4	1.3 ± 0.1	9.2 ± 5.5	10.3 ± 6.0	0.3 ± 0.4	0 [c]	0
Dryas heath	6.1	2	3.0 ± 1.4	> 100 (*n*=2)	5.3 ± 1.9	17.3 ± 8.8	0.7 ± 0.2	0.8 ± 0.1	16.5 ± 8.9	17.3 ± 8.8	0	0	0
Salix snow bed	7.2	3	1.3 ± 0.6	84 ± 22 (*n*=3)	4.9 ± 1.1	16.3 ± 10.6	0.7 ± 0.0	0.6 ± 0.3	15.7 ± 10.5	14.8 ± 10.3	1.6 ± 1.6	0	0
Grassland	19.8	6	3.7 ± 2.3	72 ± 16 (*n*=5)	6.5 ± 2.8	19.1 ± 8.3	1.1 ± 0.5	1.2 ± 0.6	17.9 ± 8.1	14.1 ± 4.9	5.0 ± 6.2	2.0 ± 0.4 (n=2)	8.4 ± 7.2 (*n*=2)
Fen	2.6	8	19.6 ± 12.5	55 ± 11 (*n*=7)	7.5 ± 3.3	22.9 ± 8.5	1.5 ± 0.7	5.3 ± 4.5	17.5 ± 9.0	14.3 ± 5.6	8.5 ± 6.6	7.2 ± 5.0 (*n*=6)	7.4 ± 4.3 (*n*=7)
Bog	0.08	2	79.5 ± 7.8	34 ± 2 (*n*=2)	13.2 ± 11.8	43.2 ± 9.8	2.7 ± 0.5	32.7 ± 6.8	11.2 ± 15.6	13.2 ± 11.8	29.3 ± 21.4	0	0
Riverbed	1.3	1	0	> 100 (*n*=1)	0.24	0.67	0.1	0	0.67	0.67	0	0	0
Barrens	10.0	0	0	?	0	0	0	0	0	0	0	0	0
Abrasion Plateau [e]	0.55	—	***0.9 d***	***?***	***1.0***	***2.4***	***0.2***	***0.1***	***2.3***	***2.5***	***0***	***0.2***	***0***
Mountain shadow [f]	6.9	—	***1.0***	***?***	***0.6***	***1.9***	***0.2***	***0.1***	***1.8***	***1.9***	***0***	***0***	***0***
Cloud shadow [g]	0.44	—	***2.3***	***?***	***3.7***	***10.8***	***0.6***	***0.6***	***10.1***	***8.3***	***2.6***	***0.4***	***1.4***
Snow [h]	4.9	—	***0.2***	***?***	***0.2***	***0.6***	***0***	***0.2***	***0.6***	***0.6***	***0***	***0.1***	***0***
Lakes and ponds	0.36	4	43.5 ± 0.7 (*n*=2)	80 ± 3 (*n*=2)	5.6 ± 2.2	14.5 ± 2.8	0.4	11.4 ± 1.3	3.1 ± 3.9	13.5 ± 1.9	1.0 ± 1.2	0	0

TABLE 1

Continued

Land cover class	Proportion of total area (%)	n	Mean ± SD depth organic layer (cm)	Mean ± SD depth active layer[a] (cm)	Mean ± SD SOC 0-30 cm (kg C m^{-2})	Mean ± SD SOC 0-100 cm (kg C m^{-2})	Mean ± SD N 0-100 cm (kg N m^{-2})	Mean ± SD Organic layer (kg C m^{-2})	Mean ± SD Mineral layer (kg C m^{-2})	Mean ± SD Active layer (kg C m^{-2})	Mean ± SD Permafrost layer (kg C m^{-2})	Mean ± SD Buried organics in active layer[b] (kg C m^{-2})	Mean ± SD Buried organics in permafrost[b] (kg C m^{-2})
Study area (weighed by land cover proportion)	100	38			2.8 ± 0.5	8.3 ± 1.8	0.5 ± 0.1	0.7 ± 0.1	7.6 ± 1.8	6.9 ± 1.4	1.4 ± 1.0	0.3 ± 0.2	0.7 ± 0.9

[a] Mean active layer depth for those profiles within each land cover class where it was reached or not reached (>100 cm) when the profile extended to the full depth of 100 cm; no values could be obtained for those profiles where the active layer and full 100 cm depth was not reached due to stones and boulders.
[b] Mean buried organics in the active layer and upper permafrost layer for those profiles within each land cover class where it was found.
[c] No cryoturbation was found in the *Cassiope* heath profiles of this study, but Elberling et al. (2008) reported SOC enrichment in the active layer below the top soil organics.
[d] All numbers in bold, italic are default values calculated from other land cover classes.
[e] Abrasion plateau used same values as Fell field.
[f] Mountain shadow values based on ⅓ Barrens, ⅓ Boulder field, and ⅓ Patchy boulder field.
[g] Cloud shadow values based on ½ Grassland and ½ Fell field.
[h] Snow values based on ¾ Barrens and ¼ Fell field.

snow (late seasonal snow fields at high elevation) occurred at elevations and locations corresponding to barrens and fell field (see Fig. 2). The abrasion plateau class is considered similar in terms of soil formation to the fell field class. Areas of mountain shadow (~7%) overlap with barrens, boulder field, and patchy boulder field. Another area of shadow caused by clouds (<1%) is situated in an area of grasslands and fell fields. Rough default values are calculated based on the estimated proportion of different land cover classes in these unsampled and/or unclassified areas (see Table 1). The associated uncertainties can have only a marginal effect on the overall calculations for the Zackenberg study site due to the low SOC storage in these higher elevation classes.

The mean SOC storage in the top 100 cm of soils at the Zackenberg study site is 8.3 ± 1.8 kg C m^{-2} (Table 1). About 0.65 kg C m^{-2} is on average stored in the top organic or peat layers and 2.8 kg C m^{-2} is stored in the top 30 cm. On average 92% of the mean 0–100 cm SOC is stored in the mineral soil horizons (7.6 kg C m^{-2}), and most of this SOC is stored in the active layer (6.9 kg C m^{-2}). If only the vegetated land cover classes are considered, mean SOC storage is 17.8 kg C m^{-2}. These land cover classes occupy, however, only ~39% of the mountainous Zackenberg study site.

The lowest SOC storage values (0–4 kg C m^{-2}) are found in land cover classes at higher elevation, which together occupy 59% of the total study area (Table 1). The highest average SOC values for the 0–100 cm soil depth are found in peatlands, in fens with a mean SOC storage of 22.9 kg C m^{-2} and in bogs with a mean of 43.2 kg C m^{-2}. Fens occupy only a small part of the total study area (2.6%), and their peat deposits are generally very shallow (20 ± 13 cm; n = 8). Bogs were not recognized separately in the land cover classification, but field observations indicate they are extremely localized and occupy only ~3% of the mapped fen area (~0.1% of the total area). Even though these bog areas have relatively thick peat deposits of 80 ± 8 cm (n = 2), they contribute little to the total SOC storage in the Zackenberg site due to their very limited spatial coverage. The vegetated land cover classes grasslands, *Salix* snowbed, *Cassiope* heath, and *Dryas* heath and the open water class lakes and ponds contain 10–20 kg C m^{-2} in the top 100 cm of the soil/sediment. The class riverbed has very low SOC storage with <1 kg C m^{-2} (Table 1).

The contribution of each land cover class to the total SOC storage in the Zackenberg study site, subdivided into top organic/peat layer and mineral layer, and into active layer and permafrost layer, is illustrated in Figure 4. The figure also shows the percentage contribution of each land cover class to the total mapped area. The grassland SOC corresponds to 46% of the total landscape SOC while it occupies 20% of the study area. The SOC-rich fen and bog sites occupy a small area (2.7%) but store 7.5% of the total SOC. The widespread higher elevation classes that occupy nearly 60% of the area contribute only ~15% to the total SOC storage in Zackenberg.

Buried soil organic material stores 13% (1.05 kg C m^{-2}) of the total mean SOC in the top meter, subdivided into 0.32 kg C m^{-2} in the active layer and 0.73 kg C m^{-2} in the upper permafrost. This material is found mainly in fen deposits, but also in grassland sites and in one fell field site.

The total soil N storage (0–100 cm) has a similar distribution in the landscape as SOC. Lowest values (0–0.5 kg N m^{-2}) are found in land cover classes at higher elevation and highest values in peatlands, with a mean N storage in the fens of 1.5 and in the bogs of 2.7 kg N m^{-2} (Table 1).

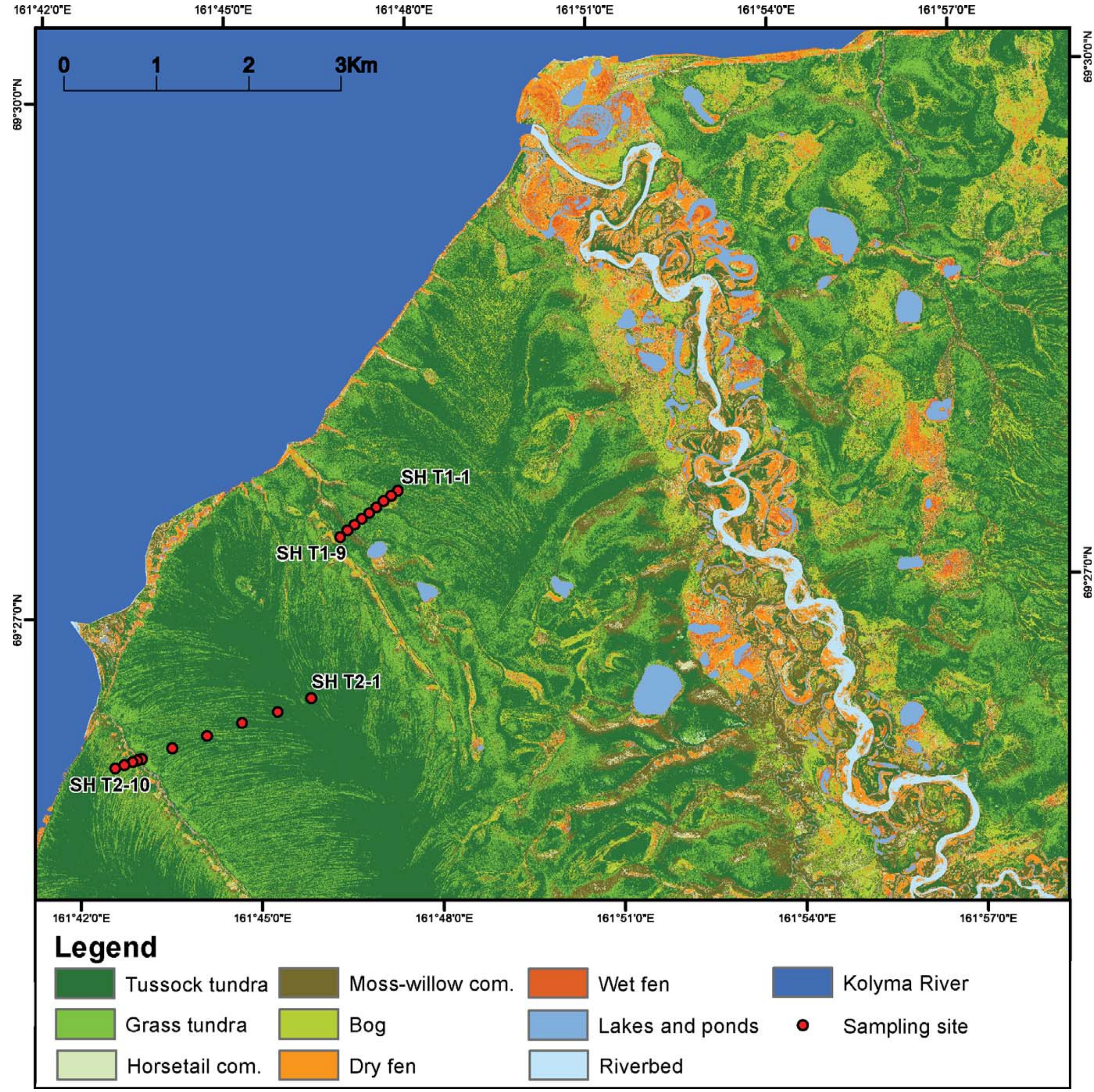

FIGURE 3. Distribution of land cover classes and location of transects and profile sites in Shalaurovo, Russia. Coordinate system UTM Zone 57N. [$150]

SOC STORAGE AND LANDSCAPE UPSCALING IN NE SIBERIA

The overall accuracy of the land cover classification in the Shalaurovo study site (Fig. 3), determined with 52 independent ground truthing points, is 90%. The calculated kappa index of agreement is 0.88. The mean SOC storage for each of the land cover classes and their different soil horizons as well as the weighed average for the whole land area is presented in Table 2.

The mean landscape-level SOC storage at Shalaurovo for the 0–100 cm soil depth interval is 30.0 ± 2.0 kg C m^{-2} (Table 2). About 10.4 kg C m^{-2} is stored in the top organic and peat layers and 11.1 kg C m^{-2} is stored in the top 30 cm. On average, 65% of the total SOC 0–100 cm is stored in the mineral soil horizons (19.5 kg C m^{-2}) and 72% of the total in the active layer (21.4 kg C m^{-2}). Deeper cryoturbated organic matter store about 30% (9.1 kg C m^{-2}) of the total SOC at Shalaurovo, subdivided between active layer with 6.3 kg C m^{-2} and permafrost layer with 2.8 kg C m^{-2} (Table 2).

The highest SOC values for the 0–100 cm soil depth in Shalaurovo were found in bogs with 56.2 kg C m^{-2} followed by lakes and ponds (53.5 kg C m^{-2}), moss-willow communities (32.5

TABLE 2

Mean SOC storage estimates (kg C m^{-2}) and total N for the Shalaurovo study site (NE Siberia), by land cover classes and soil horizons.

Land cover	Proportion of total area (%)	n	Mean ± SD depth organic layer (cm)	Mean ± SD depth active layer (cm)	Mean ± SD SOC 0–30 cm (kg C m^{-2})	Mean ± SD SOC 0–100 cm (kg C m^{-2})	Mean ± SD N 0–100 cm (kg N m^{-2})	Mean ± SD Organic layer (kg C m^{-2})	Mean ± SD Mineral layer (kg C m^{-2})	Mean ± SD Active layer (kg C m^{-2})	Mean ± SD Permafrost layer (kg C m^{-2})	Mean ± SD Buried organics in active layer[b] (kg C m^{-2})	Mean ± SD Buried organics in permafrost[b] (kg C m^{-2})
Riverbed[a]	1.7	—	***0***	***>100***	***0.6***	***4.6***	***0.1***	***0***	***4.6***	***4.6***	***0***	***0***	***0***
Tussock tundra	46.5	7	11 ± 7	59 ± 12	10.0 ± 2.0	29.0 ± 4.0	1.8 ± 0.2	4.4 ± 2.5	24.6 ± 2.8	22.0 ± 5.9	7.0 ± 4.9	13.2 ± 5.6 (n=6)	5.9 ± 5.2 (n=6)
Grass tundra	17.5	7	5 ± 2	63 ± 8	7.9 ± 0.8	21.3 ± 3.9	1.6 ± 0.2	2.3 ± 0.9	19.0 ± 4.4	17.0 ± 3.0	4.5 ± 2.6	5.1 ± 2.1	4.3 ± 2.3 (n=3)
Dry fen	6.5	2	26 ± 4	62 ± 26	8.0 ± 2.2	20.7	1.2	6.2 ± 0.1	14.4	15.7	5.1	4.7 (*n*=1)	5.1 (*n*=1)
Bog	9.5	1	~200	42	24.3	56.2	2.8	56.2[c]	0.0	32.2	24.0	0	0
Wet fen	1.4	1	115	60	3.5	27.2	1.0	27.2[d]	0	17.3	9.9	0	0
Horsetail	3.3	1	4	104	9.5	17.8	1.7	1.9	15.9	17.8	0	0	0
Moss-willow	10.9	1	9	37	13.4	32.5	1.7	3.5	29.1	16.5	16.0	0	0
Lakes and ponds[e]	***2.7***	—	—	—	***16.1***	***53.5 ± 77.2***	—	***53.5 ± 77.2***	***0***	***53.5 ± 77.2***	***0***	***0***	***0***
Study area (weighed by land cover proportion)	100	20			11.1 ± 0.7	30.0 ± 2.0	1.7 ± 0.1	10.4 ± 1.7	19.5 ± 1.1	21.4 ± 2.5	8.6 ± 1.7	6.3 ± 2.5	2.8 ± 0.9

[a] Default values in bold, italic for Riverbed from similar study site in Taymir Peninsula (J. Palmtag, unpublished material).
[b] Mean buried organics in the active layer and upper permafrost layer for those profiles within each land cover class where it was found.
[c] Total storage in the bog profile down to the diffuse, cryoturbated, peat-mineral subsoil contact at ~200 cm is 84.7 kg C m^{-2}.
[d] Total storage in the wet fen profile down to the peat-mineral subsoil contact at 115 cm is 36.4 kg C m^{-2}.
[e] Default values in bold, italic for Lakes and ponds used from Holocene thermokarst in Schirrmeister et al. (2011); mean SOC 0–30 cm calculated as 30 % of mean SOC 0–100 cm.

Table 3

Mean SOC storage estimates (kg C m^{-2}) and total N for the Cherskiy study sites (NE Siberia), by land cover classes and soil horizons.

Land Cover	Proportion of total area [a] (%)	*n*	Mean ± SD depth organic layer (cm)	Mean ± SD depth active layer (cm)	Mean ± SD SOC 0–30 cm (kg C m^{-2})	Mean ± SD SOC 0–100 cm (kg C m^{-2})	Mean ± SD N 0–100 cm (kg N m^{-2})	Mean ± SD Organic layer (kg C m^{-2})	Mean ± SD Mineral layer (kg C m^{-2})	Mean ± SD Active layer (kg C m^{-2})	Mean ± SD Permafrost layer (kg C m^{-2})	Mean ± SD Buried organics in active layer [b] (kg C m^{-2})	Mean ± SD Buried organics in permafrost [b] (kg C m^{-2})
Larch woodland	42.9	6	13 ± 4	49 ± 20	9.5 ± 2.9	17.3 ± 5.7	1.2 ± 0.4	4.0 ± 1.4	13.3 ± 6.0	11.9 ± 2.1	5.5 ± 4.7	4.2 ± 4.0 (*n*=2)	8.4 ± 3.3 (*n*=3)
Alder thicket	7.1	1	3	68	6.0	17.3	1.5	1.0	16.3	12.3	5.0	0	0
Shrub moss-lichen tundra	21.4	3	6 ± 2	71 ± 15	7.1 ± 3.6	21.5 ± 2.9	1.7 ± 0.2	2.3 ± 0.8	19.1 ± 3.0	17.9 ± 3.1	3.6 ± 4.3	11.1 ± 4.4	0
Fen	21.4	3	76 ± 86	53 ± 11	7.8 ± 5.3	23.5 ± 3.4	1.5 ± 0.5	13.1 ± 6.9 [c]	10.5 ± 9.3	13.1 ± 3.3	10.4 ± 2.2	2.3 (*n*=1)	0
Bog	7.1	1	> 175	29	5.1	28.7	1.5	28.7 [d]	0	4.7	24.0	0	0
Study area (weighed by land cover proportion)	100	14			8.1 ± 1.8	20.3 ± 2.2	1.4 ± 0.2	7.1 ± 1.8	13.2 ± 3.1	13.0 ± 1.3	7.4 ± 2.0	3.1 ± 1.5	1.8 ± 1.7

[a] Total area based on proportion of soil profiles in the transects.
[b] Mean buried organics in the active layer and upper permafrost layer for those profiles within each land cover class where it was found.
[c] Storage in one of the fen profiles down to the peat-mineral contact at 175 cm is 49.6 kg C m^{-2}.
[d] Storage in the bog profile down to 175 cm is 60.5 kg C m^{-2}; the basal peat-mineral subsoil contact was not reached.

kg C m^{-2}), tussock tundra (29.0 kg C m^{-2}) and wet fens (27.2 kg C m^{-2}). Grass tundra, horse tail communities, and dry fens have lower mean SOC values (17.8 to 21.3 kg C m^{-2}). The only really low SOC values are inferred for the exposed riverbeds (Table 2). Tussock tundra is the most dominant land cover class in Shalaurovo with 46% coverage and 45% of the total SOC 0–100 cm (Fig. 5). Bogs occupy only 9.5% of the area but are with 18% the second largest SOC pool in the landscape.

For the study sites near Cherskiy, we used transect-based upscaling. The mean SOC storage 0–100 cm is 20.3 ± 2.2 kg C m^{-2} (Table 3). Mean storage in the active layer is 13.0 ± 1.3 kg C m^{-2}. Mean SOC values for the upland land cover classes larch woodland, alder thicket, and shrubby moss-lichen tundra range between 17.3 and 21.5 kg C m^{-2},which is similar to those reported in the upland classes (excluding tussock tundra) for Shalaurovo (see Table 2). Cherskiy fens also have similar storage to those in Shalaurovo, but the bog site at Cherskiy has lower SOC content than the bog site at Shalaurovo. This difference is largely explained by very loose peat deposits (low bulk density) in the top 30 cm in the Cherskiy alas depression bog site compared to the compacted (high bulk density) peat in the polygon rim bog site at Shalaurovo. Deeper cryoturbated organics store about 24% (4.9 kg C m^{-2}) of the total SOC at Cherskiy, with 3.1 kg C m^{-2} in the active layer and 1.8 kg C m^{-2} in the permafrost layer (Table 3).

The highest soil N storage in Shalaurovo was found in the bog site with 2.8 kg N m^{-2}, while all the other land cover classes, including those at Cherskiy, show consistently a very similar N content between 1.0 and 1.8 kg N m^{-2} except the riverbed class with 0.1 kg N m^{-2} (Tables 2 and 3).

RADIOCARBON DATING

The radiocarbon dating results for the Zackenberg study site are summarized in Table 4. There is a positive correlation between age and depth of dated samples ($p < 0.05$). An outlier is the relatively young age of 1741 cal yr B.P. for the basal peat at a depth of 85–90 cm in a palsa bog, which can be explained by thick layers of almost pure segregated ice in the profile. No inverted relationships between age and soil depth occur within the five profiles that have multiple dates. It should be noted, however, that only C-enriched materials have been dated from the deeper mineral subsoil horizons. There are discernible patterns related to land cover type as well as landscape position in this mountainous area. All current fens have shallow peat deposits (20–37 cm) with young basal dates. Deeper C-enriched material is mostly found as buried layers in fen areas located at the base of active mountain slopes. They are found at depths of 35–99 cm and have ages of 1473–4004 cal yr B.P. A buried organic layer at a depth of 50–60 cm in a fell field site has an age of 4993 cal yr B.P. The oldest radiocarbon ages are obtained from deep C-enriched material found under some grassland sites and a fen/pounus site in the central valley. Dates at 50–80 cm depth range between 3929 and 7904 cal yr B.P.

Radiocarbon dates for Shalaurovo and Cherskiy are given in Table 5. At these study sites there is only a nearly significant correlation between age and depth ($p = 0.057$), if all samples are considered together. This is due to the fact that the thicker peat deposits at fen and bog sites have relatively young dates. Similarly, the sediment sequence at the willow site also has relatively young dates. An old age of 3396 cal yr B.P. is obtained for the surface peat of a polygon rim bog. At this site, wind abrasion seems to have exposed old fen peat at the surface, a typical feature in many frost-heaved peat deposits (Zoltai, 1995). The combined age-depth correlation for radiocarbon dates in peatland and willow sites, excluding this outlier, is strong ($p < 0.05$). A clear age-depth pattern is also found in mineral soils ($p < 0.05$). As in Zackenberg, no inverted dates occur within the seven profiles with multiple dates. A cryoturbated organic pocket in the active layer of a tussock tundra site has a date of 388 cal yr B.P. (45–50 cm). This date is much younger than the SOC in the directly adjacent mineral subsoil horizon at the same site (2230 cal yr B.P.). Dates for the organically enriched layers at the upper permafrost table at 47–78 cm range between 1011 and 3571 cal yr B.P. Dates between 3303 and 10,003 cal yr B.P. are obtained from cryoturbated organic pockets in the permafrost layer (65–115 cm).

The dating results from NE Greenland and NE Siberia provide similar age ranges suggesting that landscape and soil processes have operated over roughly the same time periods, that is, burial of C-enriched materials since the early Holocene and peatland development mostly during the later part of the Holocene.

SOIL CHEMICAL ANALYSES

Both the NE Greenland and NE Siberian samples have low inorganic C contents. The low carbonate content is indicated from LOI 950 °C measurements giving on average a weight loss, calculated from the total dry sample weight, of 1.05% ± 0.5% (n = 163) in Zackenberg and of 1.11% ± 0.3% (n = 101) in Shalaurovo/Cherskiy.

Organically enriched layers or pockets buried or cryoturbated into the mineral subsoil horizons were identified in the field. About 88% of these field observations on the presence/absence of C-enriched material in the mineral subsoil were subsequently confirmed by chemical analyses. We defined the sample as being C-enriched when %C increased with >30% compared to the surrounding mineral subsoil samples. Calculations on C stocks in organically enriched layers or pockets in the mineral subsoil are based on the laboratory results (see Tables 1–3).

The organically enriched samples in mineral soil horizons at Zackenberg have a %C content of 5.26 ± 2.53, which is significantly higher than the mineral subsoil samples with %C values of 1.06 ± 0.64 (t-test, $p < 0.05$). Similar differences are observed for the Shalaurovo/Cherskiy sites. Here the %C in organically enriched samples is 5.88 ± 5.76, which is also significantly higher than the %C of 1.16 ± 0.47 observed in the adjacent mineral subsoil samples (t-test, $p < 0.05$).

Figure 6, parts A–F, shows the C/N ratios for mineral soils, peatland soils, and representative individual profiles from NE Greenland and NE Siberia, subdivided into top soil organic/peat, buried C-enriched, and mineral subsoil samples. These results indicate both clear similarities as well as some significant differences. In both study areas, the C/N values of top soil organic and peat samples are significantly higher than those from the mineral horizon samples ($p < 0.05$). In Zackenberg the mean C/N ratios of the buried C-enriched materials and mineral subsoil samples show no statistical difference ($p = 0.9$). This pattern is consistent among the many fen profiles with C-enriched deeper horizons (see Fig. 6, part C), but quite variable in three affected grassland sites. In Shalaurovo/Cherskiy, the C/N ratios of C-enriched cryoturbated soil pockets are significantly higher than those of the mineral subsoil samples ($p < 0.05$). The organically enriched samples from the mineral subsoil horizons at Shalaurovo/Cherskiy display a strong positive correlation between %C and C/N ratio values ($p < 0.05$), indicating that the fraction of C-enriched material compared to the mineral subsoil fraction is an important determining factor for the C/N ratio.

Discussion

The estimated mean SOC storage of 30.0 ± 2.0 kg C m^{-2} in the 0–100 cm depth interval for the tundra site at Shalaurovo (NE Siberia) can be compared with a few other detailed studies in tundra regions with continuous permafrost that used similar land cover classification upscaling techniques to arrive to weighed averages of landscape storage. Michaelson et al. (1996) report a much higher mean SOC storage of ~50 kg C m^{-2} for the top meter of tundra soils in the Kuparuk Basin in N Alaska. Coastal plain and foothills tundra soils average 62 kg C m^{-2} and 44 kg C m^{-2}, respectively, partly because of high levels of cryoturbation (see also Ping et al., 2008). Only ~6% of the Kuparuk Basin corresponds to barren mountain slope and alpine slope areas with much lower SOC storage (4 and 10 kg C m^{-2}, respectively). The Shaularovo estimate is very similar to the mean SOC storage for the same depth interval (0–100 cm) of 33.8 kg C m^{-2} reported for the Tulemalu Lake area in the central Canadian Arctic (Hugelius et al., 2010). However, the landscape and soil horizon partitioning is somewhat different between these areas, with 56% of all SOC in Tulemalu stored in bogs and fens (land coverage of 37%) compared to 19% in Shalaurovo (land coverage of 11%), whereas only 17% of all SOC in Tulemalu was stored in cryoturbated pockets compared to 30% in Shalaurovo. Zubrzycki et al. (2013) report mean SOC storage in the top meter of 29 kg C m^{-2} for the Holocene river terrace and 14 kg C m^{-2} for the active floodplain of the Lena Delta (N Siberia). The value for Holocene river terrace, constituting a similar time interval of soil development, is very similar to that for Shalaurovo.

For the taiga sites near Cherskiy, our weighed average of landscape level SOC storage in the 0–100 cm depth interval is 20.3 ± 2.2 kg C m^{-2}. This value is based on simple transect-based upscaling. Even though care was taken to establish transects across representative land cover types following field reconnaissance, upscaling uncertainties are greater. Hugelius et al. (2010) found a ~10% difference in land cover classification–based and transect-based upscaling of the mean SOC storage at Tulemalu Lake in the central Canadian Arctic. Our mean SOC estimate for the active layer in the upland land cover classes of the Cherskiy site is 13.7 ± 1.5 kg C m^{-2}, of which 66%–91% is found in the mineral horizon. These values are similar to those reported in Mergelov and Targulian (2011), who provide estimates of 15.1 kg C m^{-2} and 60%–90% for these same variables based on soil map upscaling. The estimate of 20.3 ± 2.2 kg C m^{-2} for Cherskiy is somewhat lower than the one reported for "lowland" areas (~22 kg C m^{-2}) and higher than the one reported for "upland" areas (~10 kg C m^{-2}) of the boreal intermontane forest in a regional-scale study of Alaska (Johnson et al., 2011).

The mean landscape level SOC storage for the top meter in tundra and alpine slope soils of Zackenberg (NE Greenland) is only 8.3 ± 1.8 kg C m^{-2}, much lower than in the lowland tundra site of Shalaurovo (NE Siberia) and most of the other areas described above. This difference can be largely explained by the fact that 59% of the Zackenberg study area is located at higher elevations with mostly barren ground and low SOC contents. However, clear differences remain when considering only the SOC values for the vegetated parts of the landscape (comparisons based on SOC storage in the Zackenberg and Shalaurovo sites, which have been sampled and upscaled by the same techniques). The mean SOC storage for the vegetated land cover classes at Zackenberg is 17.8 kg C m^{-2}, compared to 29.8 kg C m^{-2} at Shalaurovo (these estimates exclude riverbeds and lakes/ponds). SOC-rich fens and bogs occupy a much smaller proportion of the landscape in Zackenberg (~3%) than in Shalaurovo (~11%).

Furthermore, the contribution of buried organic-rich material in the mineral subsoil horizons to the total SOC storage is lower

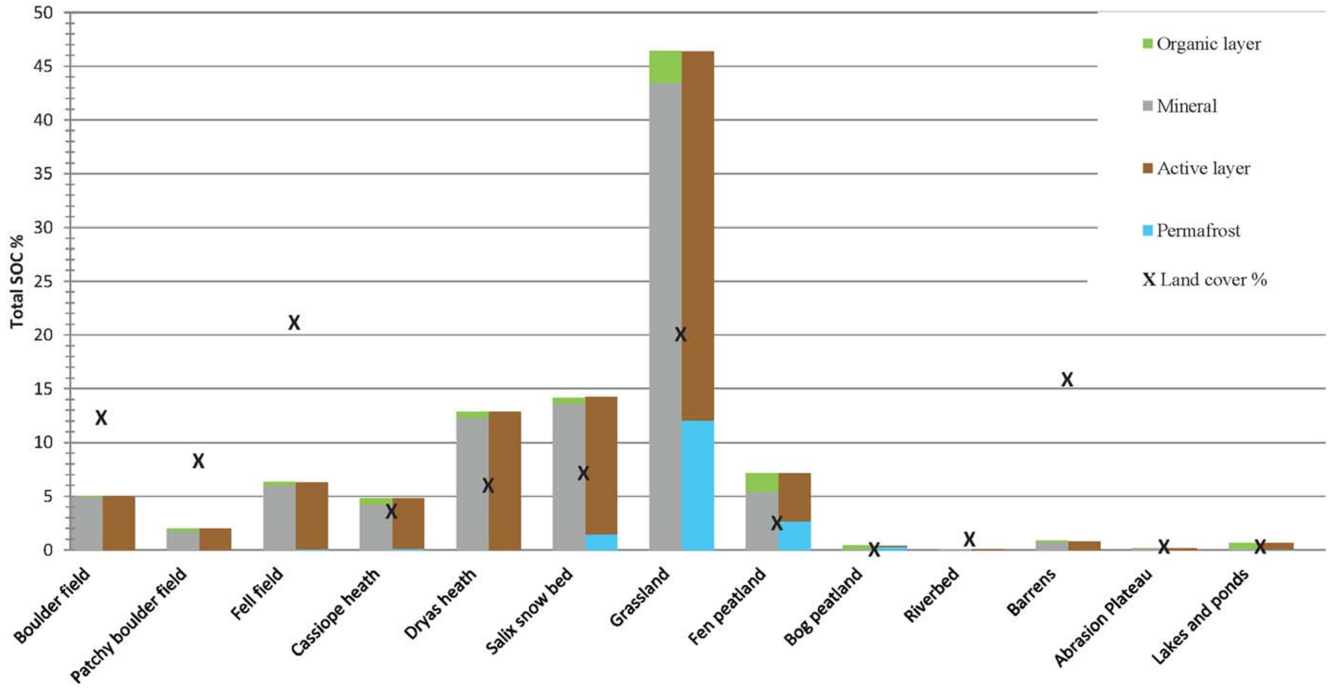

FIGURE 4. Proportional contribution of each land cover class, subdivided in the first bar in top organic or peat layer and mineral layer and in the second bar into active layer and permafrost layer, to the total soil organic carbon (SOC) carbon storage in 0–100 cm depth for the Zackenberg study site. The unsampled and unclassified areas of mountain shadow, cloud shadow, and snow were added to the default classes as described in Table 1. The "X" shows the percentage occupied by the each land cover class as a proportion of the total area. [this figure and fig. 5, together, are $150.]

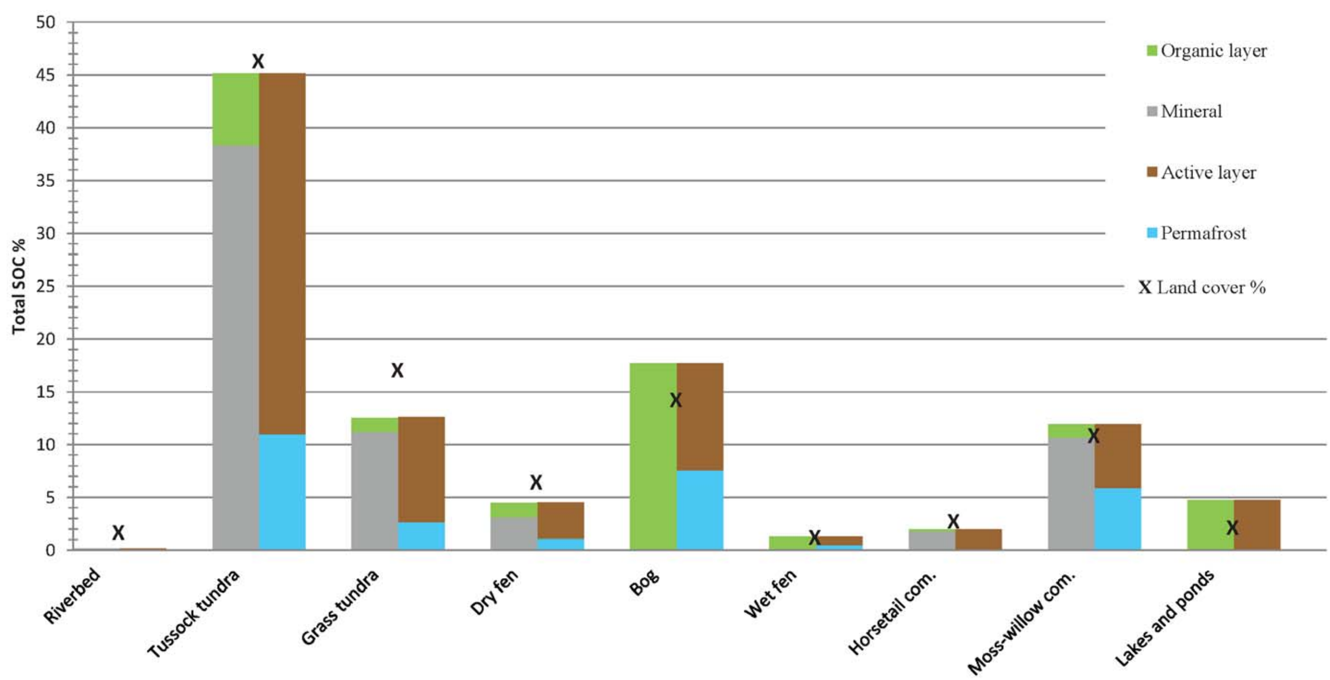

FIGURE 5. Proportional contribution of each land cover class, subdivided in the first bar in top organic or peat layer and mineral layer and in the second bar into active layer and permafrost layer, to the total SOC carbon storage in 0–100 cm depth for the Shalaurovo study site. The "X" shows the percentage occupied by the each land cover class as a proportion of the total area.

in Zackenberg (~13%) compared to Shalaurovo (~30%). A direct comparison of mean SOC storage between similar land cover classes, the grassland in Zackenberg (19.1 kg C m^{-2}) and the grass tundra in Shalaurovo (21.3 kg C m^{-2}), shows only minor differences. Our results for Zackenberg compare favorably to a previous study in the same area that considered SOC storage in the 0–50 cm soil depth of the main vegetated land cover classes (Elberling et al., 2004). Their reported value of 11.0 kg C m^{-2} is similar to the one of 9.3 kg C m^{-2} that we obtain for the same land cover classes and depth interval in this study. Our results are also similar to those from Horwath Burnham et al. (2010), who estimated a SOC storage of 9.0 kg C m^{-2} for a depth of the active layer or down to the water table using Normalized Difference Vegetation Index (NDVI)–based upscaling for a study area near the Thule Air Base in NW Greenland.

The estimated landscape-level mean soil N storage for the 0–100 cm depth interval are 1.8, 1.4, and 0.5 kg N m^{-2} for Shalaurovo, Cherskiy, and Zackenberg, respectively. These values as well as those for the individual land cover classes at all sites mirror closely the SOC content estimates, with high SOC values significantly correlated to high total N values ($p < 0.001$). Highest values were found in bogs with up to 2.8 kg N m^{-2}. The bog site in Cherskiy (1.5 kg N m^{-2}) has a relatively low value due to the low bulk density of the peat in the upper 30 cm of the profile. Intermediate soil N pools were found in the land cover classes fens, tussock and grassland tundra types, horsetail and moss-willow communities, and larch woodlands, with values ranging between 1.0 and 1.8 kg N m^{-2}. Relatively low values around 0.7–0.8 kg N m^{-2} are found in the heath and snowbed communities at Zackenberg. The lowest values of ≤0.5 kg N m^{-2} were almost exclusively confined to elevated areas with sparse vegetation in Zackenberg (and the riverbeds in Siberia).

This study highlights the importance of including all land cover classes in providing landscape level or regional estimates for mean SOC storage, particularly in a mountainous environment. Large portions of these latter areas are characterized by barren or patchy vegetation classes with very low SOC values. In this sense, even the Zackenberg study area (determined by the extent of the land cover classification map) cannot be considered representative for the Zackenberg River catchment as a whole or for the unglaciated land masses of NE Greenland, as it includes an unusually extensive area of productive grasslands and fens (Meltofte and Rasch, 2008).

Cryoturbation is an important process that significantly increases SOC storage in permafrost soils (Bockheim, 2007; Ping et al., 2008; Tarnocai et al., 2009). Our comparison of the lowland study sites in NE Siberia and the mountainous site in NE Greenland allows for a detailed analysis of the C-enriched pockets and layers in mineral subsoil horizons. The oldest dated organically enriched cryoturbated soil pockets indicate that this process has been occurring since at least 10,003 cal yr B.P. in Shalaurovo (NE Siberia) and 7904 cal yr B.P. in Zackenberg (NE Greenland). Radiocarbon dating of C-enriched material in upland soils reveals a good correlation between age and depth, with no inverted ages in individual soil profiles with multiple ages. The deeper C-enriched material found in the upper permafrost layer is older than material found in the transient or active layers. Bockheim (2007) found a similar pattern in permafrost soils of N Alaska, ascribing the older ages of the permafrost layer cryoturbations to a deeper active layer during the early-middle Holocene Hypsithermal.

This study also reveals differences in burial history of the C-enriched materials in mineral subsoil horizons, suggesting a polygenetic origin for these pockets/layers. In Shalaurovo and Cherskiy, the warped, irregularand involuted character of the C-enriched cryoturbations in both active layer and upper permafrost layer (as observed in pits) clearly suggest cryoturbation processes resulting from freeze-thaw cycles in fine-grained soil textures (Bockheim and Tarnocai, 1998). In about 80% of the upland soils in Shalaurovo and 50% of the upland soils in Cherskiy, a significant accumulation of C-enriched material was also observed in the permafrost transition layer. The often lenticular appearance of these layers supports the suggestion by Mergelov and Targulian (2011) that these are at least partly formed through the process of retinization, or the illuviation and retention of dissolved organic carbon (DOC) at the permafrost table. Indeed, the latter authors found an increased fraction of hydrophilic compounds (66%) in these layers compared to that in cryoturbations within the active layer (~57%). However, as stated by the authors, the fact that 34% of the C-enriched layers at the permafrost transition table still consist of hydrophobic fractions points to a polygenetic origin of this material, with part of the organics being deposited at these depths by other processes. Bockheim and Tarnocai (1998) describe accumulation of fibrous and partially decomposed SOM on the permafrost table as resulting from gelifluction or involutions spreading laterally across the permafrost table in association with ice-wedge and polygon formation.

Most of the deeper C-enriched material found in the Zackenberg soils has a different origin. This material is particularly abundant in fen and grassland profiles located directly under active mountain slopes. The C-enriched material appears most often as layers that can be followed for some distance over the length of exposures even though the appearance can be somewhat irregular and warped as affected by freeze-thaw cycles. We propose that these layers represent previously stable ground surfaces with vegetation/soil development that were subsequently covered by minerogenic colluvial deposits originating from reactivation and transport of uphill slope deposits. Cryoturbation in Zackenberg seems mostly restricted to the fine-textured upper horizons of eolian origin in some grassland (this study) and *Cassiope* heath (Elberling et al., 2004) soil profiles of the lower central valley. The buried organics in the fell field site are most likely the result of solifluction as it is located on a 5° slope.

The polygenetic origin of the deeper C-enriched materials in NE Siberian and NE Greenland study sites is reflected in C/N ratios, which in this study are used as a proxy for the degree of SOM decomposition. The C/N ratios of peat deposits have been shown to decrease over time due to cumulative anaerobic decay (Kuhry and Vitt, 1996; McKane et al., 1997). Similarly, organic and mineral horizons of tundra soils release CO_2 during aerobic decomposition, while N is retained, thereby lowering the C/N ratios (Ping et al., 1998). However, it is also well-documented that C/N ratios of SOM are affected by the original type of plant litter (e.g., Kuhry and Vitt, 1996; Vardy et al., 2000). Therefore, changing plant communities at a site over time might also contribute to varying C/N ratios. In all our study sites, the C/N ratios of organic soil layers as well as peat layers were significantly higher than those from buried C-enriched materials and mineral subsoil horizons. In the NE Siberian sites, C/N ratios of cryoturbated C-enriched soil pockets were also significantly higher than those of mineral subsoil horizons. A similar pattern was reported by Hugelius et al. (2010) for cryoturbated mineral permafrost soils in the Tulemalu Lake area (central Canadian Arctic), with C/N ratios of O-horizons > cryoturbated C-enriched pockets > mineral subsoil. We ascribe this pattern to cryoturbation in which relatively fresh top organic soil

TABLE 4

Summary of radiocarbon dating results for peat/gyttja and C-enriched materials in the mineral subsoil horizons for selected soil profiles in Zackenberg (NE Greenland), grouped according to land cover type (and landscape position).

Profile site [a]	Depth	Layer [b]	Description	Age ^{14}C yr BP	Age cal. yr BP [c]	Lab. no.
Grassland sites						
ZK1-5	50–60	AL	C-enriched material in mineral subsoil (central valley)	3620 ± 30	3929	Poz-39964
ZK1-4	50–60	TL	C-enriched material in mineral subsoil (central valley)	4360 ± 35	4924	Poz-42971
ZK2-1	75–80	PL	C-enriched material in mineral subsoil (central valley)	6920 ± 40	7748	Poz-39965
Fell field site						
ZK2-7	50–60	AL	C-enriched material in mineral subsoil (on slope)	4415 ± 35	4993	Poz-39969
Peatland sites						
ZK1-2	30–35	AL	Basal peat in fen (near coast)	1730 ± 35	1641	Poz-42970
ZK12-13B	56–57	AL	Basal gyttja in wetland pond (near coast)	2190 ± 30	2236	Poz-51417
ZK1-2B	0–10	AL	Surface peat of palsa bog (near coast)	Modern	<0	Poz-41075
ZK1-2B	85–90	PL	Basal peat in palsa bog (near coast)	1805 ± 30	1741	Poz-41076
ZK2-2	22–24	AL	Basal peat in fen (central valley)	2055 ± 30	2021	Poz-41077
ZK2-2	55–60	PL	C-enriched material in mineral subsoil (central valley)	7080 ± 40	7904	Poz-39967
ZK2-2B	74–80	PL	C-enriched material in mineral subsoil (central valley)	5340 ± 35	6120	Poz-39968
ZK2-6	35–45	AL	C-enriched material in mineral subsoil (below slope)	2685 ± 30	2785	Poz-42972
ZK6-1	69–75	TL	C-enriched material in mineral subsoil (below slope)	3475 ± 35	3753	Poz-42975
ZK3-0	20	AL	Basal peat in fen (below slope)	375 ± 30	441	Poz-39970
ZK3-0	57–65	TL	C-enriched material in mineral subsoil (below slope)	3405 ± 35	3652	Poz-39971
ZK3-0	90–96	PL	C-enriched material in mineral subsoil (below slope)	3505 ± 35	3774	Poz-39972
ZK3-2	30–32	AL	Basal peat in fen (below slope)	1170 ± 35	1098	Poz-42973
ZK3-2	55–65	PL	C-enriched material in mineral subsoil (below slope)	3430 ± 30	3680	Poz-42974
ZK4-1	35–37	AL	Basal peat in fen (below slope)	840 ± 30	747	Poz-39973
ZK4-1	55–60	TL	C-enriched material in mineral subsoil (below slope)	1595 ± 30	1473	Poz-39974
ZK4-1	98–99	PL	C-enriched material in mineral subsoil (below slope)	3670 ± 35	4004	Poz-39975

[a] For location of profile sites, see Figure 2.
[b] AL = sample from active layer; TL = sample from transitional layer; PL = sample from the upper permafrost layer.
[c] Estimated median age of the highest probability interval using Oxcal 4.2 (calendar years before 1950).

material is rapidly incorporated into deeper layers by freeze-thaw processes and prevented from rapid decomposition (Bockheim and Tarnocai, 1998; Kaiser et al., 2007). In contrast, the C/N ratios of SOM in organically enriched buried layers in the fen profiles at Zackenberg (NE Greenland) do not display higher values than the immediately adjacent mineral subsoil horizons. These layers seem to represent periods of surface stability with normal vegetation/soil development where the SOM could undergo its normal decomposition pathway, before being only gradually buried by reactivated slope materials.

TABLE 5

Summary of radiocarbon dating results for basal top organic/peat and C-enriched materials in the mineral subsoil horizons for selected soil profiles in Shalaurovo and Cherskiy (NE Siberia), grouped according to land cover type.

Profile site [a]	Depth	Layer [b]	Description	Age ^{14}C yr BP	Age cal. yr BP [c]	Lab. no.
			Shalaurovo sites			
Tussock tundra sites						
SH T2-5	45–50	AL	C-enriched material in mineral subsoil	325 ± 30	388	Poz-38344
SH T2-5 (bis)	45–50	AL	SOC in non-cryoturbated mineral subsoil	2210 ± 30	2230	Poz-39963
SH T2-1	19–29	AL	Base of top organic layer	Modern	< 0	Poz-38340
SH T2-1	50–55	TL	C-enriched material in mineral subsoil	1105 ± 35	1011	Poz-38341
SH T2-2	60–65	TL	C-enriched material in mineral subsoil	1555 ± 35	1462	Poz-38343
SH T1-1	65–70	PL	C-enriched material in mineral subsoil	3100 ± 35	3303	Poz-41073
Grass tundra sites						
SH T1-9	70–78	TL	C-enriched material in mineral subsoil	1950 ± 40	1901	Poz-38339
SH T2-10	47–52	TL	C-enriched material in mineral subsoil	2010 ± 35	1960	Poz-38342
SH T1-5	62–70	TL	C-enriched material in mineral subsoil	3335 ± 35	3571	Poz-39960
SH T1-5	90–95	PL	C-enriched material in mineral subsoil	6130 ± 40	7024	Poz-39961
SH T1-5	110–115	PL	C-enriched material in mineral subsoil	8870 ± 50	10003	Poz-38407
Peatland sites						
SH T1-2B	10–20	AL	Surface peat of polygon rim bog	3170 ± 40	3396	Poz-38334
SH T1-2B	140–145	PL	Peat of polygon rim bog	4170 ± 40	4710	Poz-38335
SH T1-3	60–65	TL	Peat in fen	315 ± 30	387	Poz-38338
SH T1-3	110–115	PL	Basal peat in fen	1155 ± 35	1071	Poz-38336
Moss-willow site						
SH T2-7	15–20	AL	Peat layer in sediment	755 ± 30	687	Poz-38346
SH T2-7	37–45	TL	Peat layer in sediment	855 ± 30	760	Poz-38348
SH T2-7	145–155	PL	Peat layer in sediment	2100 ± 35	2072	Poz-38345
			Cherskiy sites			
Peatland sites						
CH T6-5	26–33	AL	Peat in fen	95 ± 35	112	Poz-38353
CH T6-5	105–105.5	PL	Peat in fen	1825 ± 35	1763	Poz-38352
CH T6-5	175–175.5	PL	Basal peat in fen	2625 ± 35	2754	Poz-38408
CH T6-4	40–41	PL	Peat in bog	1330 ± 40	1265	Poz-38351
CH T6-4	122	PL	Peat in bog	2370 ± 35	2401	Poz-38349
CH T6-4	165–170	PL	Peat in bog	2570 ± 35	2724	Poz-38350

[a] For location of profile sites along Shalaurovo transects, see Figure 3.
[b] AL = sample from active layer; TL = sample from transitional layer; PL = sample from the upper permafrost layer.
[c] Estimated median age of the highest probability interval using Oxcal 4.2 (calendar years before 1950).

Conclusions

This study presents new SOC data from the High Arctic and northern Eurasia, two sectors that have previously been identified as having low pedon coverage. The aim of this study is to describe the SOM quantity and characteristics at the landscape level in two contrasting areas within the continuous permafrost zone.

The estimated mean SOC storage for the top meter in tundra and alpine slope soils of the mountainous Zackenberg study site (NE Greenland) is two to four times lower than in the lowland taiga and tundra soils of the Cherskiy and Shalaurovo study sites (NE Siberia). The main reason for this difference is that more than half of the study area at Zackenberg is represented by higher elevation, largely barren ground with very low SOC content. This emphasizes the need to include all major land cover classes as well as their proportional representation within the landscape when providing estimates of mean SOC storage for a particular study area.

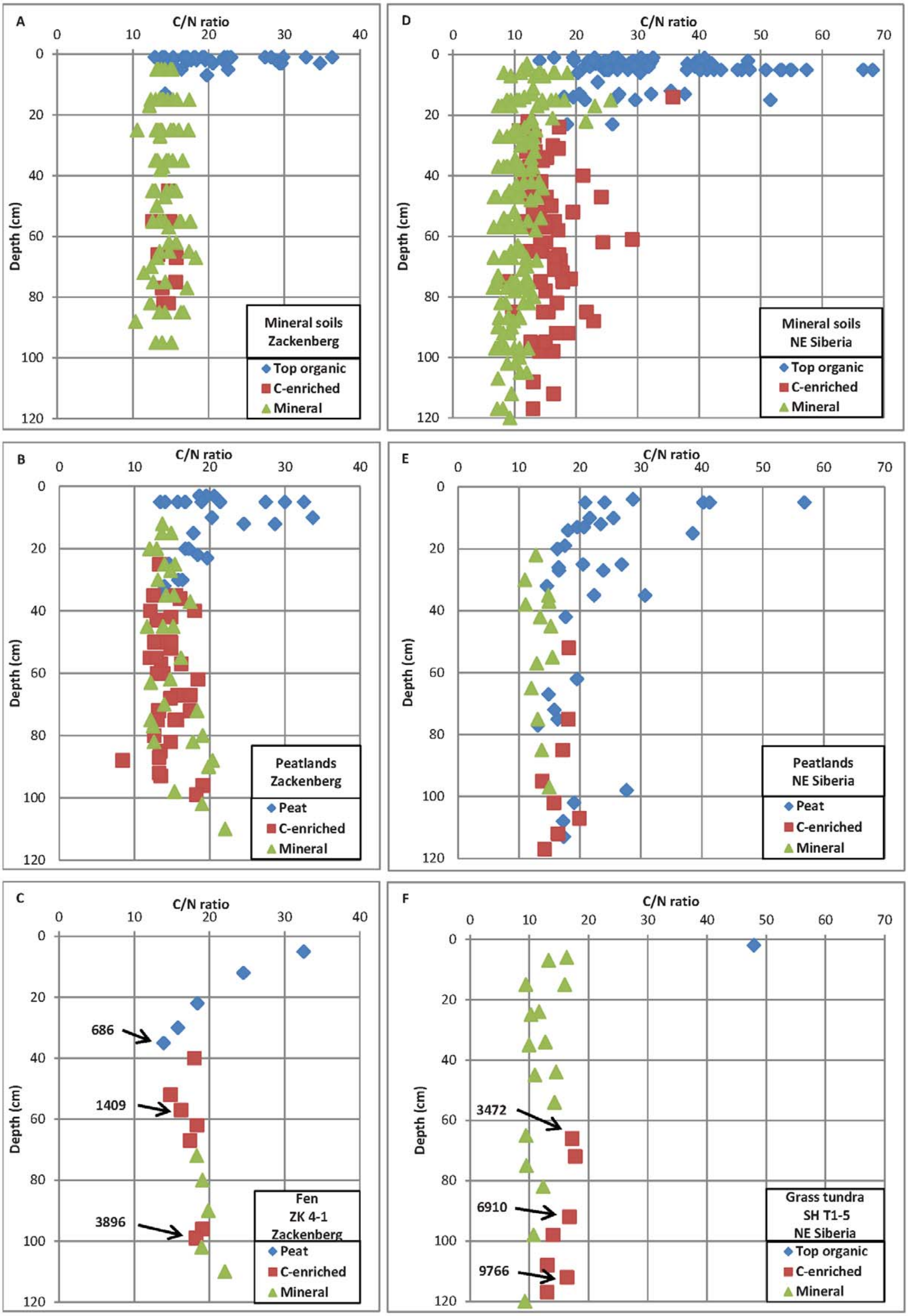

FIGURE 6. (A–F) Carbon/nitrogen (C/N) weight ratios subdivided into top organic/peat layer, C-enriched materials buried in mineral subsoil and mineral subsoil for mineral soils, peatland soils, and selected profiles from NE Greenland and NE Siberia. Ages in cal yr BP are shown for a fen profile in Zackenberg and for a grass tundra profile in Shalaurovo. [$150]

In Zackenberg, slope processes were the main mechanism burying organic-rich surface layers into the mineral subsoil. These layers are particularly abundant in fen areas at the foot of slopes, where periods of surface stability lead to vegetation/soil development followed by gradual burial under minerogenic material resulting from uphill slope reactivation. We hypothesize that SOM in these layers was exposed to relatively rapid, near surface, aerobic decomposition over longer time periods prior to burial. This material is therefore relatively well decomposed. In the NE Siberian study sites, cryoturbation has been the predominant process of burial into the mineral soil horizons. In this way, relatively fresh SOM from the top soil organic layer was transferred rapidly to greater depth, where it remains in a relatively low state of decomposition. In addition to cryoturbation, retinization may have been another important process for the accumulation of C-enriched material (illuviated DOC) in the permafrost transition layer of NE Siberian soils. We therefore conclude that several processes account for incorporation of organically enriched materials into the deeper mineral soil horizons of permafrost soils. Of these, cryoturbation seems to be most efficient in sequestering larger amounts of relatively undecomposed material at greater soil depths.

The results of this study indicate large variability in the quantity and degree of decomposition of the SOM pools within the zone of continuous permafrost. Topographic and edaphic factors affect the landscape-level SOC storage and different processes of burial have an effect on SOM decomposition state. Despite an increasing number of detailed field studies, the challenge remains to upscale this variability to a northern circumpolar scale for a full assessment of the permafrost carbon pool and its vulnerability to global warming and permafrost thawing.

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