# Landscape partitioning and burial processes of soil organic carbon in contrasting areas of continuous permafrost

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## Abstract

Recent studies have shown that permafrost soils in the northern circumpolar region store almost twice as much carbon as the atmosphere. Since soil organic carbon (SOC) pools have large regional and landscape-level variability, detailed SOC inventories from across the northern permafrost region are needed to assess potential remobilization of SOC with permafrost degradation and to quantify the permafrost carbon-climate feedback on global warming.

This thesis provides high-resolution data on SOC storage in five study areas located in undersampled regions of the continuous permafrost zone (Zackenberg in NE Greenland; Shalaurovo and Cherskiy in NE Siberia; Ary-Mas and Logata in Taymyr Peninsula). The emphasis throughout the five different study areas is put on SOC partitioning within the landscape and soil horizon levels as well as on soil forming processes under periglacial conditions. Our results indicate large differences in mean SOC 0–100 cm storage among study areas, ranging from 4.8 kg C $m^{-2}$ to 30.0 kg C $m^{-2}$, highlighting the need to consider numerous factors as topography, geomorphology, land cover, soil texture, soil moisture, etc. in the assessment of landscape-level and regional SOC stock estimates.

In the high arctic mountainous area of Zackenberg, the mean SOC storage is low due to the high proportion of bare grounds. The geomorphology based upscaling resulted in a c. 40% lower estimate compared to a land cover based upscaling (4.8 vs 8.3 kg C $m^{-2}$, respectively). A landform approach provides a better tool for identifying hotspots of SOC burial in the landscape, which in this area corresponds to alluvial fan deposits in the foothills of the mountains. SOC burial by cryoturbation was much more limited and largely restricted to soils in the lower central valley. In the lowland permafrost study areas of Russia the mean SOC 0–100 cm storage ranged from 14.8 to 30.0 kg C $m^{-2}$. Cryoturbation is the main burial process of SOC, storing on average c. 30% of the total landscape SOC 0–100 cm in deeper C-enriched pockets in all study areas. In Taymyr Peninsula, the mean SOC storage between the Ary-Mas and Logata study areas differed by c. 40% (14.8 vs 20.8 kg C $m^{-2}$, respectively). We ascribe this mainly to the finer soil texture in the latter study area. Grain size analyses show that cryoturbation is most prominent in silt loam soils with high coarse silt to very fine sand fractions. However, in profiles and samples not affected by C-enrichment, C concentrations and densities were higher in silt loam soils with higher clay to medium silt fractions.



Key words: soil organic carbon, total nitrogen, permafrost, cryoturbation, geomorphology, land cover classification, slope processes, texture, upscaling, carbon/nitrogen ratio.

# Sammanfattning

Aktuella studier visar att permafrostjordar i den norra cirkumpolära regionen lagrar nästan dubbelt så mycket kol som jordens atmosfär. Då mängden markbundet organiskt kol (soil organic carbon, SOC) är mycket variabel både på regional och landskapsnivå så behövs det detaljerade inventeringar från hela den nordliga permafrostregionen för att fastställa potentiell (re)mobilisering av SOC med degraderande permafrost och för att kvantifiera permafrostkolets återkoppling till den globala uppvärmningen.

I denna avhandling presenteras högupplösta data på SOC-lagring från fem studieområden belägna inom den kontinuerliga permafrostzonen i områden som tidigare varit underrepresenterade i internationella databaser (Zackenberg i NÖ Grönland, Shalaurovo och Cherskiey i NÖ Sibirien; Ary-Mas och Logota på Tajmyrhalvön). Studierna har fokuserat på SOC-fördelningen inom landskapet och mellan markhorisonter samt på periglaciala markprocesser.

Våra resultat visar på stora skillnader mellan studieområdena, de genomsnittliga SOC-förråden (0–100 cm djup) sträcker sig från 4.8 kg C $m^{-2}$ till 30.0 kg C $m^{-2}$. Detta belyser behovet av att överväga ett stort antal faktorer så som topografi, geomorfologi, marktäcke, jordtextur och jordfuktighet i skattningen av SOC-förråd regional och landskapsnivå.

I det högarktiska bergsområdet i Zackenberg är den genomsnittliga SOC-lagringen låg på grund av den höga andelen kal mark. I detta område resulterade en geomorfologibaserad kartering i en ca. 40% lägre skattning jämfört med en baserad på marktäcke (4.8 vs. 8.3 kg C $m^{-2}$, respektive). En metod baserad på geomorfologiska landformer är ett bättre verktyg för att identifiera 'hotspots' för SOC-lagring; i detta fall alluviala avlagringar vid foten av branta sluttningar. Begravning av SOC genom kryoturbation var mycket mer begränsad och till stor del inskränkt till jordar i den nedre centrala dalen. I de låglänta studieområdena i Ryssland varierade de genomsnittliga SOC-förråden mellan 14.8 till 30.0 kg C $m^{-2}$ (0–100 cm djup). Kryoturbation är den viktigaste lagringsprocessen av SOC då sådana markhorisonter svarar för i genomsnitt ca. 30% av det totala SOC 0–100 cm förrådet i alla studieområden.

På Taymyrhalvön skiljer sig det genomsnittliga SOC-förrådet mellan Ary-Mas och Logata med ca. 40% (14.8 vs. 20.8 kg C $m^{-2}$, respektive). Vi tillskriver detta främst till den finare jordtexturen i det senare studieområdet. Analyser av kornstorlek visar att kryoturbation är mest framträdande i siltdominerade jordar med hög fraktion grov silt till mycket fin sand. I profiler och prover som ej påverkats av C-anrikning från kryoturbation så var C koncentrationerna och C densiteten dock högre i med högre fraktion av lera till medium-silt.

## Thesis content

This thesis is based on the following papers, which will be referred to by their Roman numerals. The papers are appended at the end of the thesis. The published papers are reprinted by permission from the copyright holder.

**Paper I** Palmtag, J., Ramage, J., Hugelius, G., Gentsch, N., Lashchinskiy, N., Richter, A. and Kuhry, P., 2016: Controls on the storage of organic carbon in permafrost soil in northern Siberia. European Journal of Soil Science, 67, 478–491, doi:10.1111/ejss.12357.

**Paper II** Palmtag, J., Hugelius, G., Lashchinskiy, N., Tamstorf, M. P., Richter, A., Elberling, B. and Kuhry, P., 2015: Storage, landscape distribution and burial history of soil organic matter in contrasting areas of continuous permafrost. Arctic, Antarctic, and Alpine Research, 47, 71–88, doi:10.1657/AAAR0014-027.

**Paper III** Palmtag, J., Cable, S., Hugelius, G., Christiansen, H. H. and Kuhry, P. Improved landscape partitioning and estimates of deep storage of soil organic carbon in the Zackenberg area (NE Greenland) based on geomorphological landforms. Manuscript.

**Paper IV** Palmtag, J. and Kuhry, P. Grain size controls on cryoturbation and soil organic carbon density in permafrost-affected soils. Manuscript.

## Author contributions

**Paper I:** In Taymyr Peninsula the soil sampling was carried out by Gustaf Hugelius, Justine Ramage, Nikolay Lashchinskiy and by me. I did most of the chemical and statistical analyses as well as the writing itself, the maps and the figures/tables. The co-authors participated in the interpretation of the results and/or contributed with improvement of the text.

**Paper II** Soil sampling in the Zackenberg area was carried out by Peter Kuhry and Gustaf Hugelius while in the Siberian study area soil samples were collected by Peter Kuhry, Gustaf Hugelius, Nikolay Lashchinskiy and by me. I did most of the chemical and statistical analyses as well as the writing itself, the maps and the figures/tables. The co-authors participated in the interpretation of the results and/or contributed with improvement of the text.

**Paper III** Soil sampling in the Zackenberg area was carried out by Peter Kuhry, Gustaf Hugelius, Daiga Smeke, and by students participating in the UNIS course AG-833 "High Arctic Permafrost Landscape Dynamics in Svalbard and Greenland", including me. I did most of the chemical and statistical analyses as well as the writing itself, and the figures/tables. The landform upscaling is based on an adapted version of the original geomorphology map by Stefanie Cable and colleagues. The co-authors participated in the interpretation of the results and/or contributed with improvement of the text.

**Paper IV** This meta-analysis paper is based on soil samples from paper I, II and III. I analysed the data and led the writing of the paper. The interpretation of the results, the figures/tables and the improvement of the text were a collaborative effort.

# Contents

# 1. Introduction

Research in the northern circumpolar permafrost region, which occupies 16% of the global soil area, has increased significantly during the last decades motivated by the fact that terrestrial ecosystems in high latitudes perform an important role in the global carbon cycle. Recent studies have shown that permafrost soils in the northern circumpolar region, which are acting as carbon (C) sinks since the Pleistocene, store almost twice the size of the entire atmospheric C pool (Tarnocai et al., 2009). A recent update of soil organic carbon (SOC) storage in the northern circumpolar permafrost region gives an estimate of 1307 Pg, with an uncertainty range of 1140–1476 Pg (Hugelius et al., 2014). This region includes not only the zone of continuous permafrost, which refers to terrain where permafrost underlies 90–100% of the landscape, but also the zones of discontinuous (50–90%), sporadic (10–50%) and isolated (< 10%) permafrost. Much of this SOC pool has accumulated over decadal to millennial timescales and is often preserved in a relatively undecomposed state because of cold temperatures and often water-logged conditions, which prevented microbial decomposition (Davidson and Janssens, 2006; Hicks Pries et al., 2012).

Permafrost soils are vulnerable to degradation under future global warming and in most regions the permafrost temperatures have increased since the 1980s (IPCC, 2013). The observed warming and degradation could intensify the microbial activity and decomposition of organic matter and release more greenhouse gases into the atmosphere providing a positive feedback on climate warming (Schuur et al., 2015; Wild et al., 2016). These ecosystems undergo numerous changes and recent studies indicate that the Arctic tundra has already changed to a weaker C sink or even a C source (Belshe et al., 2013). This has happened in spite of the fact that since the 1990s the C uptake has increased in terms of plant productivity caused by warmer temperatures and longer growing seasons (McGuire et al., 2012). According to the last report from the Intergovernmental Panel on Climate Change (IPCC, 2013) it is almost certain that increased global mean surface temperatures will decrease the near-surface permafrost extent (upper 3.5 m) by 37% up to 81% by the end of the 21st century (for RCP2.6 to RCP8.5, respectively; RCP *representative concentration pathways* for greenhouse gas concentrations which are used for climate modelling). Despite the accepted fact that permafrost soils hold an enormous SOC pool vulnerable to warming, knowledge on its regional, landscape and soil profile distribution is still insufficient.

## 1.1 Aims and objectives

The overarching aim of my PhD project is to investigate the mean storage, landscape and soil horizon partitioning of SOC in several areas of continuous permafrost. A special emphasis was put on the importance of landforms, soil texture as well as different burial processes for SOC storage. In addition, some of the component studies also address phytomass C (PhC) and total nitrogen (TN) stocks, as well as the degree of decomposition of soil organic matter (SOM). The goal with the new data from field work, laboratory analyses, remote sensing and GIS applications is to increase our understanding of carbon and nitrogen pools in permafrost terrain, which can be used to improve assessments of the permafrost carbon feedback on global warming.

The fieldwork was conducted in lowland tundra, forest-tundra and northern taiga settings in Ary-Mas and Logata (Taymyr Peninsula, Paper I) and Shalaurovo and Cherskiy (NE Siberia, Paper II), and the high arctic mountainous area of Zackenberg (NE Greenland, Papers II and III). Figure 1 is showing the locations of these five study areas. The purpose of papers I and II was to improve our knowledge of landscape-level SOC content by using land cover classification (LCC) upscaling based on high resolution remote sensing imagery. The new data is an important contribution of SOC estimates, especially since the High Arctic and Eurasia have significant data gaps and are the reason for high uncertainties (Hugelius et al., 2014). However, the use of land cover based upscaling from paper II showed also some limitations, particularly in mountainous sites such as Zackenberg. Therefore, in paper III we aim to improve the previous SOC storage results by using a new geomorphological map from the Zackenberg valley (adapted from Cable et al., in prep.). We hypothesize that landforms better represent the long-term slope and depositional processes that result in deep SOC burial in this type of mountain permafrost environment. In addition, paper III presents the first SOC estimates for deeper deposits, from 1 m to 3 m depth, for the Zackenberg area. Finally, Paper IV is a meta-analysis from all our field sites, where we aim at identifying relationships between deep SOC burial and soil texture, by comparing %C and C densities of soil samples and their grain size distributions.

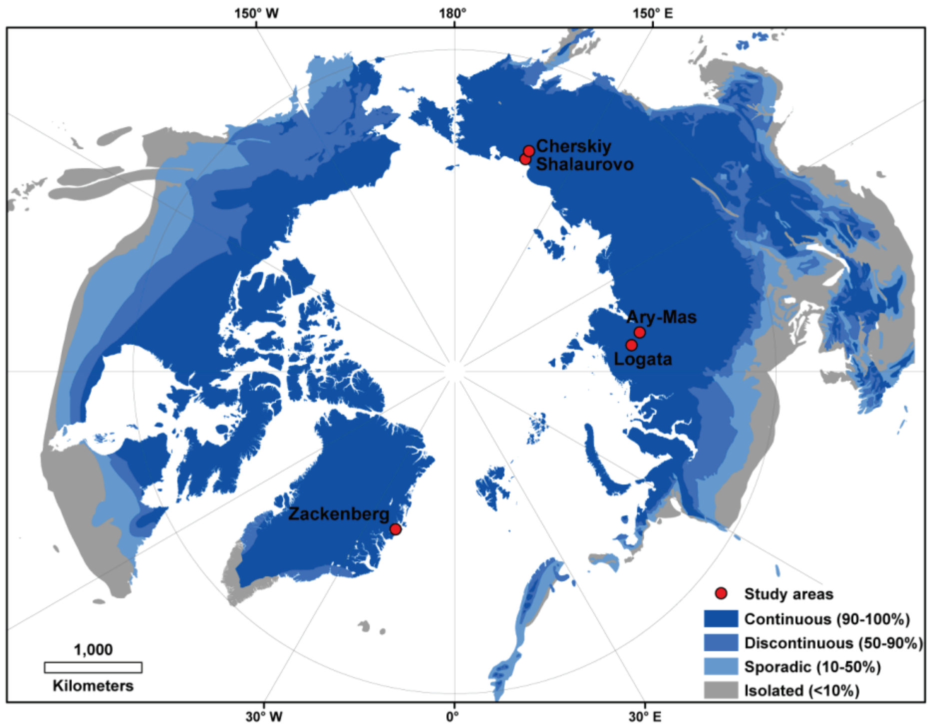



Figure 1. Location of the study areas addressed in this PhD thesis. Northern circumpolar permafrost map adapted from Brown et al. (2001). Different colours indicate the permafrost zonation.

## 1.2 The global carbon cycle

The global biogeochemical carbon cycle refers to the movement of C between the different pools that exist in the geosphere, hydrosphere, pedosphere, atmosphere and biosphere (Ruddiman, 2008). On a global scale, C exchange between the different pools has been seriously altered by human impact. Anthropogenic emissions of carbon dioxide ($CO_2$) released by e.g. burning fossil fuels, deforestation and manufacturing concrete have raised atmospheric concentrations to levels that exceed natural fluctuations over the past 400 000 years (Fig. 2), initiating a dramatic climate change (Falkowski et al., 2000). This climate change also affects the C balance of natural ecosystems. The photosynthesis and respiration rates are dependent on many factors such as temperature, soil moisture, soil oxygen concentration, $CO_2$ concentration, availability of organic matter and nitrogen, and many others. Soil respiration involves several processes such as root respiration, heterotrophic respiration, litter decomposition and SOM oxidation (Luo and Zhou, 2006).

Heterotrophic respiration is controlled by microbial organisms via decomposition of organic compounds. Under anaerobic conditions the decomposition of organic matter leads to production of methane ($CH_4$). Warming and thawing in permafrost terrain will increase the rate of decomposition of stored SOM, leading to the release of $CO_2$ and $CH_4$ depending on surface hydrological conditions.

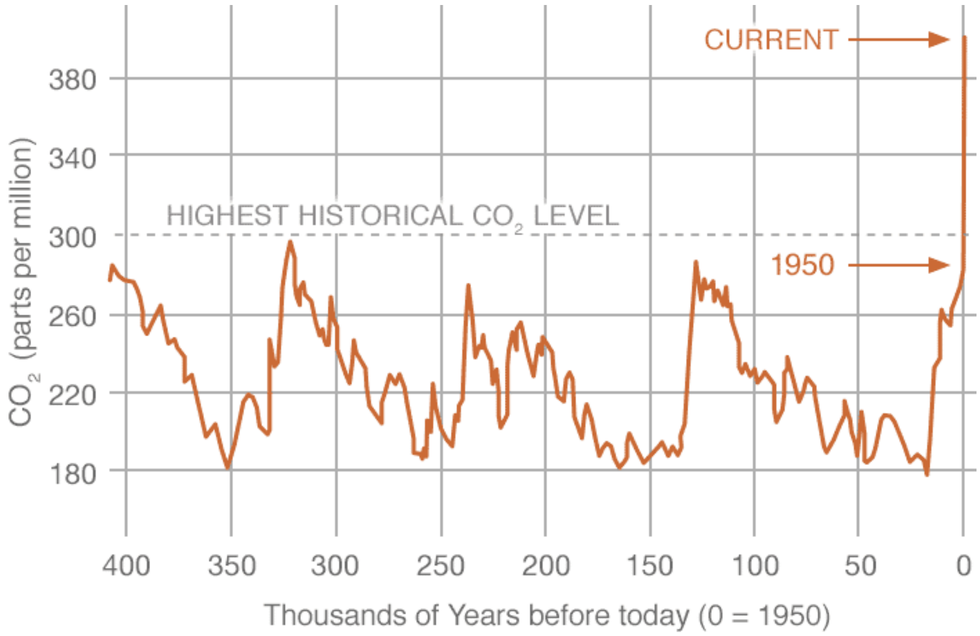



Figure 2. The global atmospheric $CO_2$ concentration in parts per million for the last 400 000 years, based on ice core samples and recent direct measurements (Credit: NOAA, www.noaa.gov).

### 1.3 The global mass of soil organic carbon

The first global soil carbon pool estimate of 400 Pg was published by Waksman in 1936. Since then, a lot of research was conducted on that topic and many new estimates were introduced (Schlesinger, 1977; Post et al, 1982; Batjes, 1996; Jobbagy and Jackson, 2000, Gruber et al. 2004). The most recent estimate was published by Köchy et al. in 2015, with a new global SOC stock estimated to be 3000 Pg of which half is located in permafrost regions (see section 1.4).

The importance of carbon stored in permafrost and the potential feedback to accelerate global warming was highlighted first in the 1990s (e.g. Gorham et al., 1991). Since then, the number of scientific publications on carbon in permafrost has increased almost exponentially (Fig. 3). In 2009, Tarnocai et al. linked circumpolar SOC data (e.g. Kuhry et al., 2002; Zimov et al., 2006; Tarnocai et al, 2007; Ping et al, 2008) and presented a total estimate of 1674 Pg SOC stored in the northern circumpolar permafrost region. The most recent SOC storage estimate for the northern circumpolar permafrost region is 1300 ± 200 Pg (Hugelius et al., 2014). Even though, SOC estimates in permafrost have slightly decreased, the recent SOC stock is equivalent to the amount of C stored in the atmosphere and all the terrestrial vegetation added together, making the permafrost C pool very important for the global climate system.

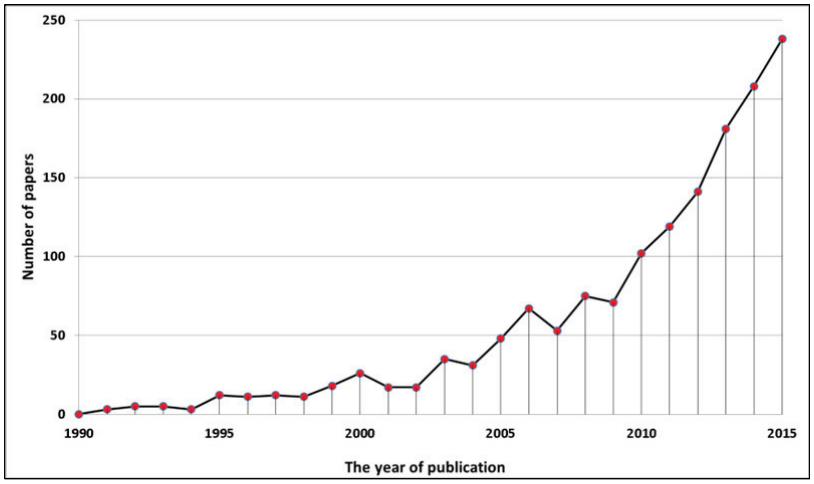


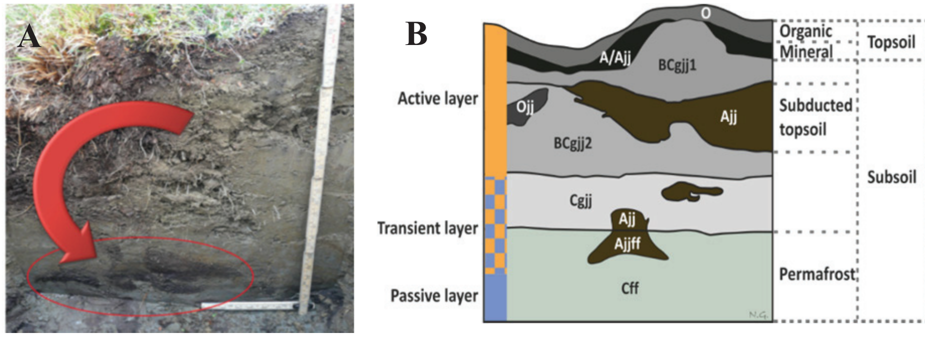
Figure 3. Indication for the number of scientific papers published between 1990 and 2015 containing the keywords “permafrost + carbon” from Web of Science.

## 1.4 Permafrost

Permafrost is perennially frozen ground (soil or rock, and includes ice and organic matter) that remains at or below 0˚C for two or more consecutive years (Van Everdingen, 1998). The northern permafrost region is widespread and occupies an area of about 18.8 million square kilometres, which is equivalent to 16% of the global soil area (Tarnocai et al., 2009). As mentioned in the introduction, not the whole permafrost region is frozen. In general, the percentage of area underlain by permafrost increases northwards while the permafrost temperature decreases. In continuous permafrost, >90% of the landscape is underlain by permafrost with a mean annual ground temperature that ranges from –1˚C to –15 ˚C (Romanovsky et al., 2010).

The uppermost ground layer of permafrost is called the active layer (AL), which thaws and refreezes seasonally. The thickness of AL ranges from a few tens of cm to several meters depending on many factors such as surface temperature, vegetation cover, snow cover, soil moisture, soil substrate, etc. Since the AL is unfrozen during the summer, it plays an important role for biochemical, hydrological and pedological processes (Kane et al., 1991).

In permafrost regions, cryoturbation is a major soil forming process and refers to all soil movements triggered by freeze-thaw cycles favoured by imperfect soil drainage and silt material (Bockheim, 2007). The mixing of various soil horizons leads to (1) subduction of organic-rich topsoil horizons into deeper layers (where colder and wetter conditions delay microbial decomposition processes) and (2) formation of a new carbon-rich topsoil layers. Both processes increase the SOC storage and often result in irregular and broken horizons and deep C-enriched pockets (Fig. 4A and 4B). The importance of cryoturbation is widely recognized and the process is included in all modern soil taxonomic systems (e.g. Turbels in the Gelisol order; Soil Survey Staff, 2014). Kaiser et al. (2007) pointed out that about 80% of the Canadian Arctic is affected by cryoturbated soils. On a circumpolar scale this has resulted in an enormous SOC reservoir, located in subducted C-enriched pockets with relatively undecomposed organic matter, which is susceptible to warming and thawing (Čapek et al., 2015; Weiss et al., 2016). However, some authors have suggested that with increased temperatures under global warming the rate of cryoturbation could increase (Bockheim et al., 2007). Furthermore, not all buried SOC is the result of cryoturbation. Slope process in mountain permafrost settings can lead to the burial of SOC layers formed under previously stable vegetated surfaces (Fig. 4C).



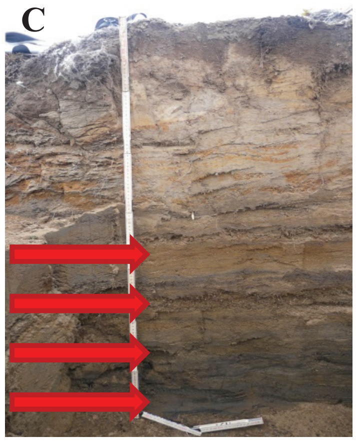




Figure 4. (A) Subduction by freeze-thaw cycles of organic-rich topsoil horizons into deeper soil layers (Photo: Juri Palmtag). (B) Cryoturbated pockets and their distribution within a soil profile (Gentsch et al., 2015). Horizon symbols according to Keys to Soil Taxonomy (Soil Survey Staff, 2010). O = organic soil material; A = mineral, organic enriched horizon; B = subsurface accumulation horizon; C = horizon with little or no pedogenic alteration; jj = evidence of cryoturbation; ff = permanently frozen soil or ice; g = strong gley features. (C) Continuous and regular buried SOC layers in alluvial fan in Zackenberg (Photo: Juri Palmtag).

# 2. Materials and methods

## 2.1 Study areas

Both study areas from Paper I are on Taymyr Peninsula, Russia (Fig. 5). Ary-Mas (72°28’N, 101°54’E) and Logata (73°25’N, 98°26’E) are located 150 km apart in the North Siberian Lowland within the typical tundra bioclimatic subzone D, corresponding to low arctic or sub-arctic tundra (Walker et al., 2005). The landscapes are characterized by polygonal tundra, meandering rivers and thermokarst lakes within the continuous permafrost zone (Schmidt, 1999). During the Quaternary Period, Taimyr Peninsula was glaciated several times but the study areas were ice-free periglacial environments during the Last Glacial Maximum (Svendsen et al., 2004). In Ary-Mas, the parent soil material is dominated by sandy fluvial-marine sediments from the Eemian sea transgression while the marine sediments in Logata are mainly silt from the Kara Sea transgression 80–60 000 years ago (Svendsen et al., 2004). The mean annual air temperature for Lake Labaz, the closest meteorological station ~80 km W–SW from Arymas, is –13.4°C. The mean annual precipitation is less than 250 mm of which 50% falls as rain during the summer months.

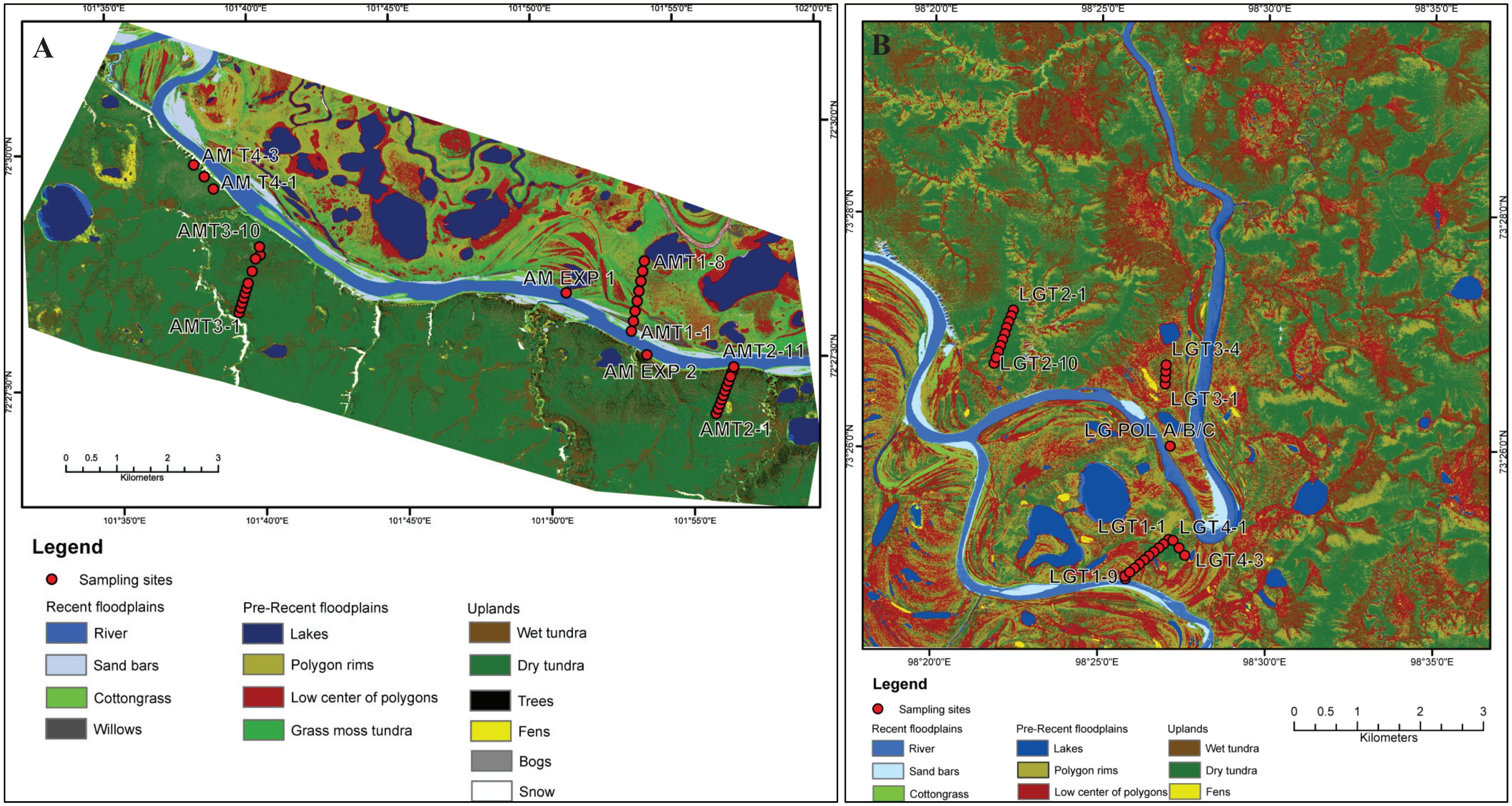



Figure 5. LCC maps from (A) Ary-Mas and (B) Logata on Taymyr Peninsula, showing different geomorphological units, land cover classes and transect based sampling sites (Palmtag et al., 2016).

The study area Zackenberg, located in NE Greenland (74°28'N, 20°34'W) is part of Paper II and Paper III (Fig. 6). It is a mountainous high-arctic landscape site within the bioclimatic subzone C (Walker et al., 2005) in the continuous permafrost zone. The Zackenberg valley was shaped by a large fault system which divided the weather-resistant Caledonian gneiss/granite bedrock in the West from the Cretaceous-Tertiary sedimentary rocks in the East (Escher and Watt, 1976). The elevation varies between 0 m a.s.l. of the Young Sound and 1372 m a.s.l. at Zackenberg Mountain peak in the West. According to Bennike et al. (2008) deglaciation of the central valley occurred prior to 11 300 cal yr BP. The parent material in the lower valley is dominated by glacial, deltaic, fluvial and alluvial deposits, while boulder fields or solifluction material dominates the slopes (Christiansen et al., 2008). The mean annual air temperature in the central valley is –9.2 °C, with 261 mm mean annual precipitation which mainly falls as snow (Hansen et al., 2008).

Shalaurovo and Cherskiy are two additional field sites from Paper II, situated along the Kolyma River in the Kolyma Lowland, NE Siberia. Shalaurovo (69°27'N, 161°48'E) is located within the bioclimatic subzone D in the southern tundra (Fig. 7) while Cherskiy (69°45'N, 161°29'E), only 80 km to the South, is located near the northern limit of the taiga in the southern boundary of bioclimatic subzone E (Walker et al., 2006). Both sites are within the continuous permafrost zone and have never been glaciated during the Pleistocene (Astakhov, 2008). The parent soil material is dominated by syngenetic Late Pleistocene deposits of aeolian, fluvial and alluvial sediments characterized by large ice wedges (Schirrmeister et al., 2011). The climate in this region is continental with a mean annual air temperature of –11.3 °C and a mean annual preciptation of 290 mm distributed almost equally between summer and winter months.

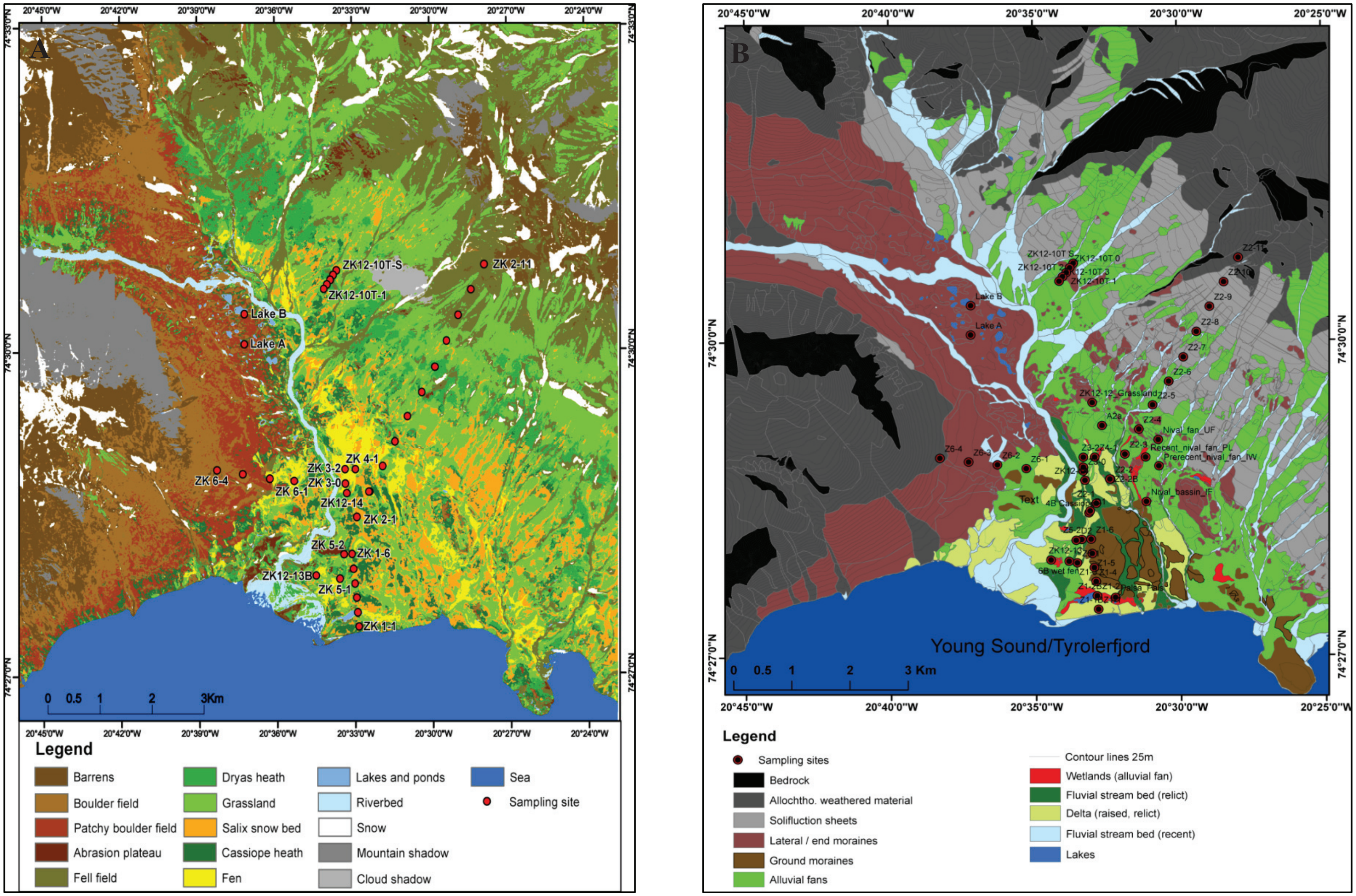



Figure 6. Land cover (A) and landform (B) classification map, with the location of transects and profile sites in Zackenberg, NE Greenland. The land cover classification is after Elberling et al. (2008). The geomorphology is adapted from Cable et al (in prep.).

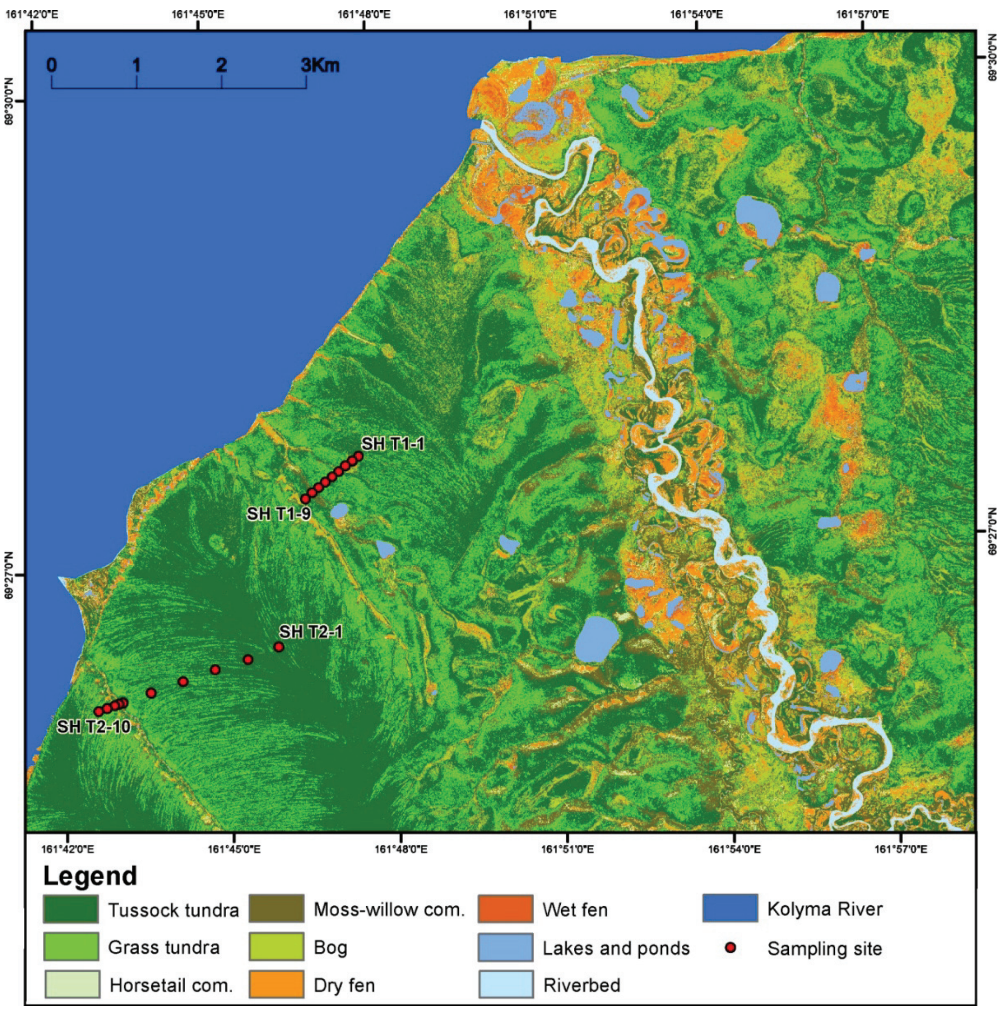



Figure 7. Land cover classification map including sampling sites from Shalaurovo, NE Siberia (Palmtag et al., 2015).

## 2.2 Field sampling

The aim with the fieldwork is to collect representative soil samples (in Taymyr Peninsula also aboveground phytomass samples), which can be used to estimate the existing SOC pool. Because of the high landscape variability in the arctic, the challenge is to ensure that all the important land cover classes, soil types and landforms are included occurring within the predefined study area. Therefore, a detailed field reconnaissance was always the first step before the actual sampling started. A stratified sampling scheme was used in which straight transects were selected with the intention to cross all the recognized major landscape elements at each study site. Once the first sampling site and the bearing of a transect was established, in accordance with the field reconnaissance, each further sampling point was set equidistantly in a predefined interval (50, 100 or 200m depending on geomorphological settings or landscape patterns) without further subjective preference using a GPS. In some cases additional pedons were sampled if small scale but important landforms were otherwise missed (e.g. palsa, pond, etc.). This semi-random stratified sampling approach combines representation of all key landscape elements while avoiding subjectively selected sampling locations by introducing a degree of randomness under the fixed-interval criterion. This pragmatic sampling strategy was developed as a solution to logistical constraints (such as time and local transport) when conducting fieldwork in remote areas since the exact location of the study area in most cases was unclear until arrival and therefore a pre-selection of sites was not possible. The fieldwork was always conducted during late summer, in 2009, 2010, 2011, 2012 and 2013. This time period was chosen to get the maximum seasonal thaw depth (active layer).

Soil sampling consisted of several different approaches with the aim to collect material to at least 1 m depth (Fig. 8). Each sampled increment was usually between 5 and 10 cm long. The top organic layer was collected at all sites (excluding peatlands) as a block which was cut out with a knife or scissors. The field volume was calculated from measured block dimensions. Due to extreme variability in micro-topography, two additional randomly selected top organic replicates were collected to improve the accuracy. The active layer was sampled using a 100 cm³ stainless core cutter which was inserted horizontally into the wall of an open soil pit. Unfrozen fen peatlands were sampled using a Russian Peat corer. Permafrost samples were collected using a steel pipe, which was manually hammered into the ground. During the field work in Zackenberg in 2013 a handheld motorized Earth Auger (STIHL BT 121) was used for sampling permafrost samples. In Taymyr Peninsula, additional biomass samples were collected and used to estimate the C stored in phytomass. After sampling, each soil profile site was carefully photographed and described with respect to active layer depth, soil moisture, topographic/catenary position (including slope and aspect), land cover and proportion of bare ground and boulders in the surroundings. In addition, individually collected soil increments were visually described for their grain size, soil type, roots, occurrence of buried soil organic matter pockets, and segregated ground ice content.

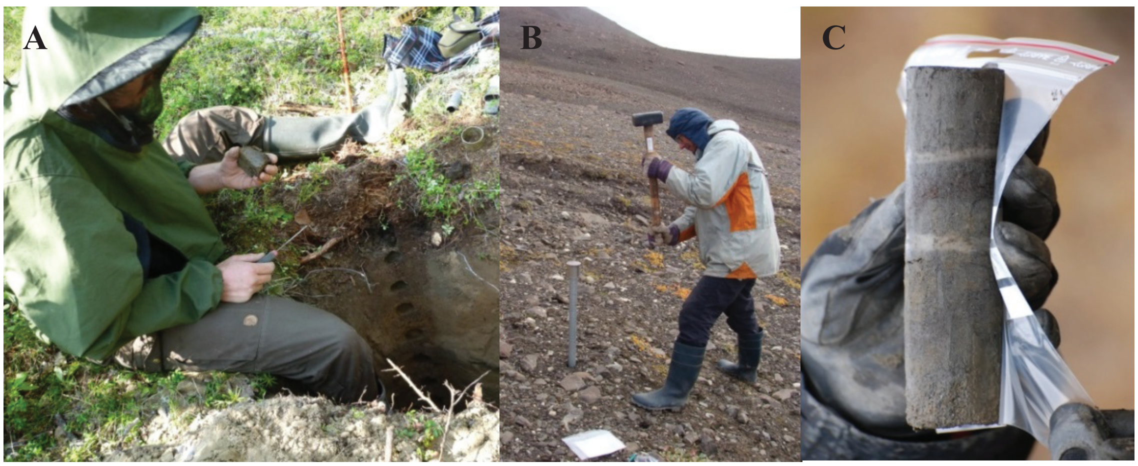



Figure 8. Photographs from field sampling: (A) Open soil pit sampling using 100 cm³ stainless core cutter. Photo: Elin Högström; (B) A steel pipe which is hammered into the soil. Photo: Gustaf Hugelius; (C) Permafrost core collected with a steel pipe. Photo: Peter Kuhry

## 2.3 Soil chemical analyses and radiocarbon dating

In order to calculate dry bulk density (DBD; g $cm^{-3}$), soil samples with known field volume were oven-dried at 70°C for at least 24 hours and, subsequently, homogenized and sieved to separate the coarse fraction (CF) of >2 mm. Next, the loss on ignition (LOI, %) method was applied to estimate the soil organic matter (SOM) content of each sample by burning representative sub-samples at 550° for 5h (Dean, 1974; Heiri et al., 2001). In addition, at least three randomly chosen samples per profile were burned for an additional 2 hours at 950 °C to determine the carbonate content. Further analysis for C and N contents and stable isotope composition were performed at the University of Vienna, Austria (Department for Chemical Ecology and Ecosystem Research), where c. 80% of all soil samples were analyzed using a EA 1110 Elemental Analyzer (CE Instruments), coupled to a Finnigan MAT DeltaPlus IRMS with a Finnigan MATConFlo II Interface. For the remaining 20% of samples, which were mainly from an additional fieldwork period in Zackenberg, we estimated organic carbon content using a polynomial regression between the LOI550 and %C from the Elemental Analyzer (Fig. 9).

We used carbon to nitrogen (weight) ratios as an indicator for SOM decomposition. Because the metabolic activity by soil organisms releases preferentially C and leaves processed N behind, the C/N ratio decreases with a higher degree of humification. Since usually deeper soil layers are older and undergo decomposition for longer periods, C/N ratios also decreases with depth (Kuhry and Vitt, 1996; Ping et al., 1998; Palmtag et al., 2015).

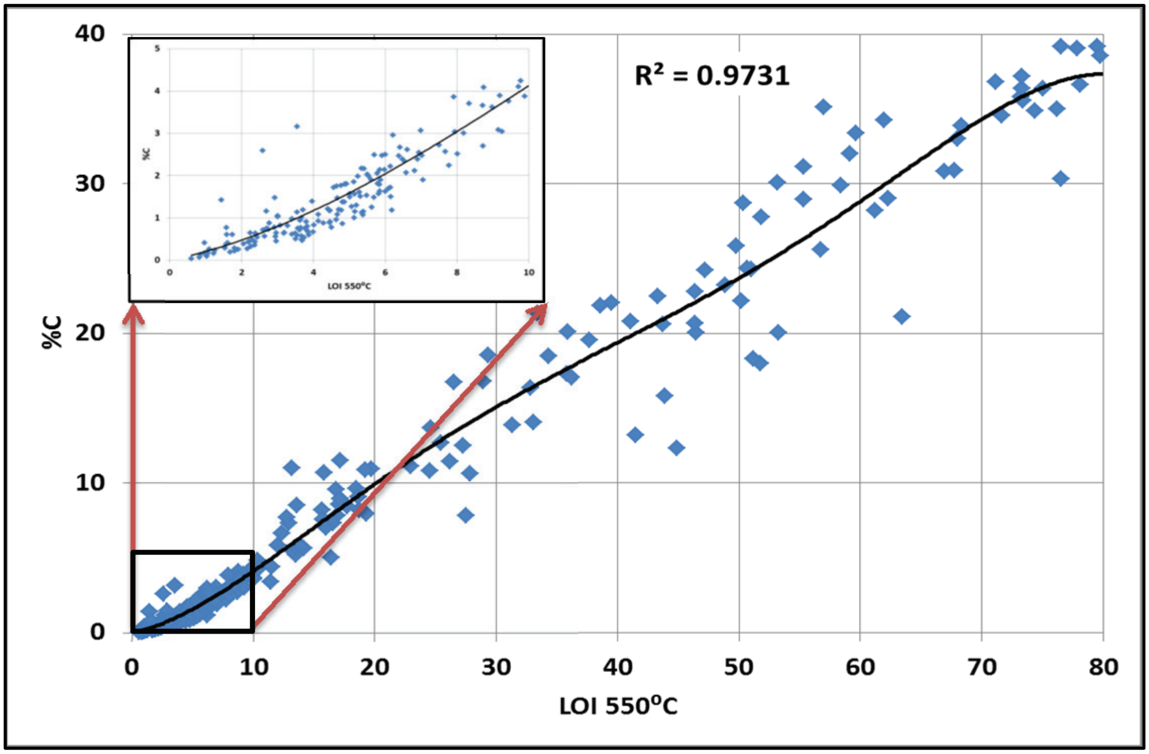


Figure 9. A polynomial regression between the LOI550 and %C.

Since one emphasis of this thesis was put on burial processes, we were interested to investigate the age of the landscape, surface stability and the soil forming processes. Accelerator mass spectrometry (AMS) $^{14}C$ dating at the Poznan Radiocarbon Laboratory, Poland was used to measure the age across the five study areas from 67 selected bulk TOC samples. The ages, expressed in calendar years before the present (cal yr BP) and indicated as the median of the largest 95% probability interval, were calibrated with the IntCall3 calibration curve using Oxcal 4.1/4.2 (Bronk Ramsey, 2010, Reimer et al., 2013).

## 2.4 Land cover classification

Produced land cover classification (LCC) maps for Ary-Mas, Logata and Shalaurovo are based on remotely sensed high resolution QuickBird imageries which were acquired in July/August 2011. QuickBird imageries have a spatial resolution of 0.6 m in panchromatic and 2.4 m in multispectral bands. Image classification was performed in ENVI 5.1 (Exelis, Boulder, CO, USA) using supervised maximum-likelihood classification. Using this approach the classes are defined manually and assigned to individual pixels in so called training areas. Once all the classes are defined, the program runs an extensive classification algorithm based on probability density functions while assuming that each training area in each band are normally distributed (Campbell, 2011). Once this step is performed, all the pixels are assigned to a specific class (Fig. 10). Any further geoprocessing, calculations and layout were performed in ArcGIS 10.1/10.2 (ESRI, Redlands, CA, USA). In the case of Zackenberg, a LCC product used in Paper II was already available (Elberling et al., 2008). For Cherskiy there were neither satellite imagery nor LCC map available and a simple transect-based approach was utilized.

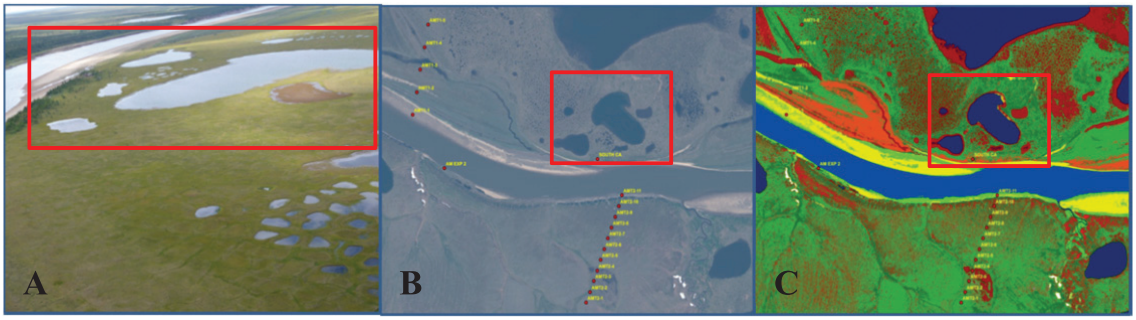



Figure 10. (A) Aerial view; (B) Original QuickBird satellite imagery with 2.4m special resolution; (C) Reclassified LCC map from the same area.

### 2.5 Soil organic carbon and total nitrogen calculations

SOC and TN contents (kg $m^{-2}$) were calculated for each collected soil sample using equations 1 and 2 (see below). The equations are based on DBD (g $cm^{-3}$), C and N concentrations (%), coarse fraction CF (>2 mm), sample thickness T (cm), multiplied by 10 for unit correction.

$$SOC = (DBD * \%\,C * (1 - CF) * T) * 10 \qquad (1)$$

$$TN = (DBD * \%\,N * (1 - CF) * T) * 10 \qquad (2)$$

Total SOC and TN storage was calculated for each profile by adding the mass from each sample to widely used reference depths of 0–30 cm, 0–100 cm, 100–200 cm and 200–300 cm, if data available. If a sample was missing, the gap was interpolated from samples directly below or above taking into account field observations. To describe the SOC partitioning in each profile, SOC was also subdivided into top organic/peat layer (OL), mineral subsoil layer (ML), active layer (AL), permafrost layer (PF) and buried organically-enriched pockets (CT). Samples were only defined as cryoturbated when the %C of the sample was substantially higher (>30%) then the surrounding mineral subsoil material. Since three top organic replicates were collected per profile, the SOC and TN contents is based on their mean in order to account for local variability. Subsequently, all profiles were grouped into thematic classes (land cover or geomorphological features).

### 2.6 Upscaling approaches

The size of each LCC map was predefined by areal extends of the available satellite imagery. The upscaling for the Cherskiy site from Paper II was transect-based, a proportional representation of land cover classes along the sampled transect, since no satellite imagery was available. The upscaling map in Paper III is based on a digital geomorphological map at 1:10 000 scale from Cable et al. (in prep.). The map was based on ortho-rectified panchromatic aerial images of 0.2 m resolution and validated by 4000 in situ waypoints.

First, the arithmetic mean SOC/TN stock and standard deviation (SD) was calculated based on all profiles belonging to each thematic class in each study area. Landscape level SOC/TN stocks are shown as a weighed mean for the whole study area and calculated from the mean values of each thematic class multiplied with the proportion of the area occupied by that class. To provide reasonable error estimates, quantitative 95% confidence intervals (CI) for landscape SOC/TN, weighed for the variance within and areal coverage of each upscaling class, were calculated using equation 3 below: where t is the upper $\alpha/2$ of a normal distribution ($t \approx 1.96$), $a_i$ the total area % of the class i, $StD_i$ is the standard deviation of the class i, $n_i$ the number of replicates in class i (Thompson, 1992).

$$CI = t * \sqrt{\sum \left( \left( {a_i}^2 * {SD_i}^2 \right) / n_i \right)} \qquad (3)$$

These CI ranges only reflect the uncertainty arising from natural variability in the environment and/or insufficient sampling of variable classes; they do not account for uncertainty associated with the errors in the land-cover upscaling products (Hugelius, 2012).

# 3. Summary of the included papers

## 3.1 Paper I

Palmtag, J., Ramage, J., Hugelius, G., Gentsch, N., Lashchinskiy, N., Richter, A. and Kuhry, P., 2016: Controls on the storage of organic carbon in permafrost soil in northern Siberia. *European Journal of Soil Science*, 67, 478–491, doi:10.1111/ejss.12357.

The objectives in Paper I were to estimate soil organic carbon (SOC) , total nitrogen (TN) and aboveground phytomass carbon (PhC) storage and their distribution across the landscape in two continuous permafrost study areas on Taymyr Peninsula (N Siberia). The research question addresses regional SOC variations as both sites are located only 150 km apart with relatively similar land cover. For upscaling, Quickbird satellite imagery was used to create land cover classification maps with an areal extend of 92.5 $km^2$ and 100.3 $km^2$ in Ary-Mas and Logata, respectively. Both areas were subdivided into geomorphological units, i.e. uplands, pre-recent and recent floodplains.

The weighed mean SOC storage for 0–100 cm depth in Ary-Mas was estimated to be 14.8 kg $m^{-2}$, which is about 40% lower than in Logata with 20.8 kg $m^{-2}$. The substantial difference is mainly ascribed to finer-textured soils in Logata (silt loam), which had on average higher %C and C/N ratios (Table 1). Gentsch et al. (2015) also reported higher Al and Fe concentrations in Logata subsoil and proposed that organo-mineral associations have resulted in the higher %C values in this study area.

Upland areas occupying c. 50% of both study areas were storing most SOC (17.5 kg $m^{-2}$ in Ary-Mas vs 25.5 kg $m^{-2}$ in Logata), with lowest SOC stocks (4.1 kg $m^{-2}$ in Ary-Mas vs 3.4 kg $m^{-2}$ in Logata) in recent floodplains occupying 10% and 5% of the areas, respectively. About 70% of the SOC was allocated within the active layer with the bulk being located in the mineral subsoil part. Cryoturbation is an important soil forming process occurring since at least the early Holocene. About 34% of the total SOC in the top meter is stored in C-enriched cryoturbated pockets in both study areas. This proportion is comparable to that reported in many other studies (Hugelius et al., 2010, Palmtag et al., 2015). Buried pockets were present in the active- and in the permafrost layer. TN stocks were 1.0 kg $m^{-2}$ in Ary-Mas and 1.3 kg $m^{-2}$ in Logata. The contribution of phytomass to total ecosystem C storage was in both areas only 2%.

A detailed comparison between these two similar and nearby located sites showed distinct differences in their mean SOC stocks. At the landscape level, large differences were observed between floodplain and upland areas. This study highlights the importance of soil texture and geomorphology, among other factors, which can have a large effect on SOC storage even on a regional scale. Therefore, large scale maps and even regional data sets describing SOC pools are usually highly simplified products with a substantial uncertainty range (Hugelius et al., 2014). Only increased number of detailed field studies can better describe this variability in carbon stocks.

Table 1. Comparison of mean %C and C/N ratios (with SD) between all mineral soil profiles from Ary-Mas and Logata, for top soil organic layer, C-enriched cryoturbated pockets and mineral subsoil samples.

Ary-Mas

| Top organic layer (n=41) | | Cryoturbated pockets (n=37) | | Mineral subsoil samples (n=108) | |
|---|---|---|---|---|---|
| Mean %C | Mean C/N ratio | Mean %C | Mean C/N ratio | Mean %C | Mean C/N ratio |
| 11.8 (10.1) | 22.2 (6.3) | 3.1 (1.0) | 16.1 (3.1) | 1.0 (1.0) | 12.1 (3.1) |

Logata

| Top organic layer (n=45) | | Cryoturbated pockets (n=57) | | Mineral samples (n=109) | |
|---|---|---|---|---|---|
| Mean %C | Mean C/N ratio | Mean %C | Mean C/N ratio | Mean %C | Mean C/N ratio |
| 20.4 (10.3) | 27.7 (8.2) | 7.1 (6.8) | 18.8 (6.2) | 2.3 (2.0) | 14.5 (2.3) |

### 3.2 Paper II

Palmtag, J., Hugelius, G., Lashchinskiy, N., Tamstorf, M. P., Richter, A., Elberling, B. and Kuhry, P., 2015: Storage, landscape distribution and burial history of soil organic matter in contrasting areas of continuous permafrost. *Arctic, Antarctic, and Alpine Research*, 47, 71–88, doi:10.1657/AAAR0014-027.

In this study we examined and compared soil organic matter quantity, landscape partitioning and geochemical characteristics in two areas of continuous permafrost, a mountainous region in NE Greenland (Zackenberg) and a lowland region with two sites in NE Siberia (Shalaurovo and Cherskiy). The results are based on 887 analysed soil samples from 72 profiles. Land cover classification maps were used to upscale the carbon (C) and total nitrogen (TN) stocks for the corresponding study areas. The presented results are shown as landscape level weighed mean values.

The Zackenberg weighed mean soil organic carbon (SOC) content at 0–100 cm was 8.3 kg C $m^{-2}$. Fens and bogs were the SOC richest classes (22.9 kg C $m^{-2}$ and 43.2 kg C $m^{-2}$, respectively) but because of the small areal extend (2.6% and 0.1%, respectively) their contribution to the whole study area storage is little (Figure 11-A). Grasslands, occupying 20% of the study area and a mean SOC content of 19.1 kg $m^{-2}$, are the most dominant contributors to the landscape with 46% of the total SOC storage. Nevertheless, Zackenberg is a mountainous area where c. 60% of the landscape is non–vegetated and located at higher elevation, which considerably lowers the mean SOC storage for the study area as a whole. In comparison, the mean SOC storage for the 2 Siberian lowland areas, Shalaurovo and Cherskiy was 30.0 and 20.3 kg $m^{-2}$, respectively. Tussock tundra, with a mean SOC 0–100 cm stock of 29.0 kg $m^{-2}$ and 46% of landscape coverage, was the most dominant land cover class in Shalaurovo accounting for 45% of the total SOC (Figure 11-B), while the Cherskiy area was dominated by larch woodland (17.3 kg $m^{-2}$ SOC 0–100 cm, 43% of the area and an estimated 37% of the total landscape storage).

An additional focus of this study was on the amount of SOC incorporated by burial processes, which was found in all study areas and varied between 12% in Zackenberg and 24–30% in Cherskiy and Shalaurovo. In Zackenberg the dominant part was buried by slope processes, while cryoturbation was mostly restricted to some fine-textured aeolian horizons in the lower central valley. The prevailing burial mechanism in the NE Siberian field areas was cryoturbation.

The C/N ratios, used as a proxy to evaluate the degree of SOM decomposition, were relatively high in the cryoturbated material of Shalaurovo and Cherskiy soils confirming the burial of fresh top organic soil material into deeper layers. The C/N ratios of buried organic layers in Zackenberg showed no difference to that of mineral subsoil samples indicating that these layers were only gradually buried by slope materials. These results showed that permafrost landscapes within the continuous permafrost are highly heterogeneous not only in terms of SOC quantity but also in SOM quality.

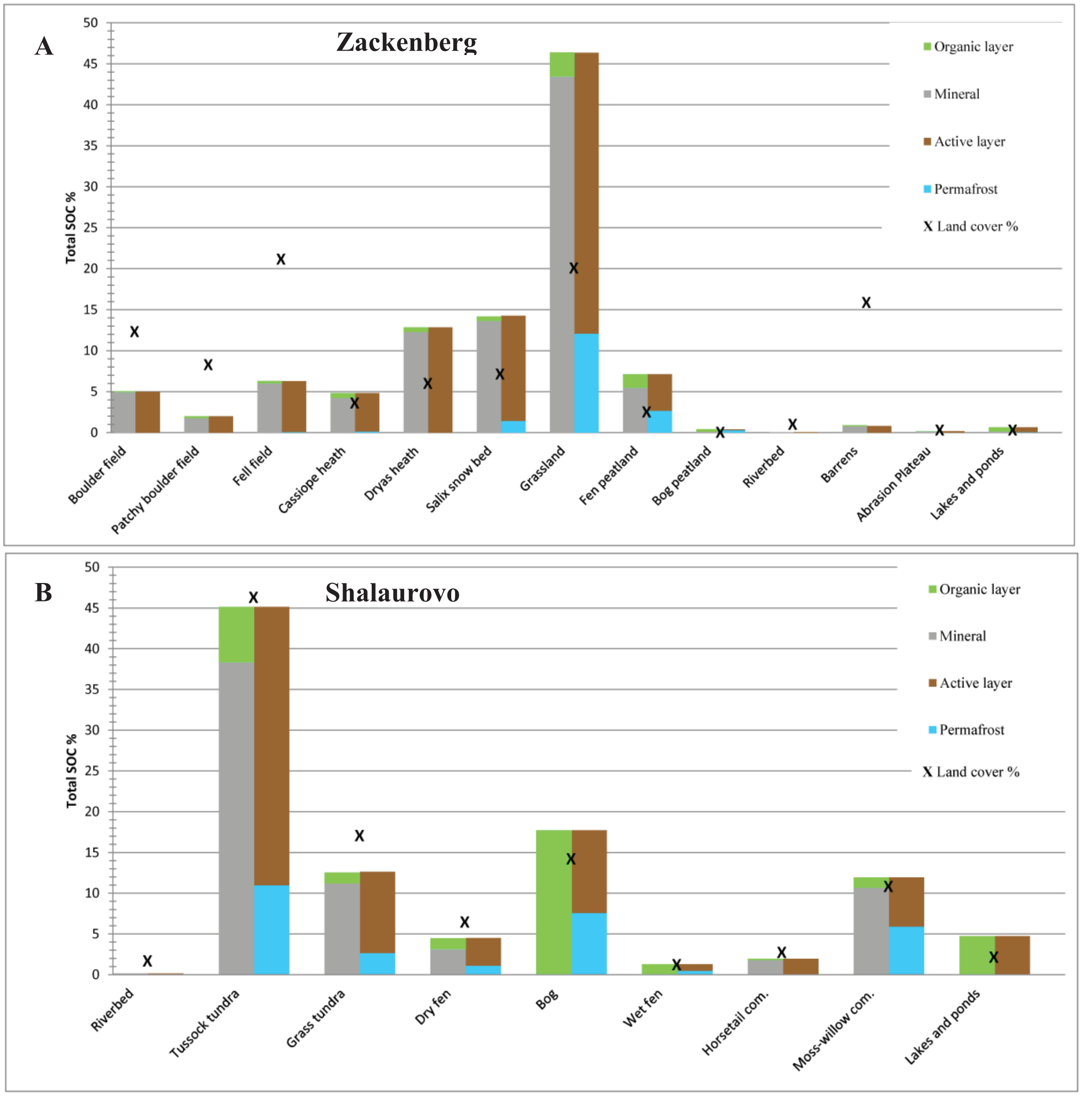



Figure 11. Proportional contribution of each land cover class to the total SOC carbon storage in 0–100 cm depth, subdivided in the first bar in top organic or peat layer and mineral layer and in the second bar into active layer and permafrost layer. The "X" shows the percentage occupied by each land cover class as a proportion of the total study area. (A) Zackenberg and (B) Shalaurovo (Palmtag et al., 2015).

### 3.3 Paper III

Palmtag, J., Cable, S., Hugelius, G., Christiansen, H. H., and Kuhry, P. Improved landscape partitioning and estimates of deep storage of soil organic carbon in the Zackenberg area (NE Greenland) based on geomorphological landforms. Manuscript.

The objective of this study was to improve the results from the previous LCC upscaling (Paper II) and evaluate the importance of geomorphology for assessing landscape level C storage in the Zackenberg study area (NE Greenland). The new mean SOC estimate to 1 m depth is 4.8 kg C $m^{-2}$, which is 42% less than the previously reported LCC-based value of 8.3 kg C $m^{-2}$. In addition, this study presents first deep storage SOC estimates for up to 3 m depth.

The main reason for the large difference in the SOC storage is the areal overestimate of land cover classes with SOC-rich soils. For example, grasslands occur in the central valley, the foothills and the mountain slopes. However, the collected pedons in this class were biased towards C-rich sites at lower elevations. From a SOC perspective, slope processes were identified as the main burial mechanism of organic-rich surface layers by creating thick fine-grained deposits in alluvial fans located in the foothills (Figure 12). We hypothesized that the landform-based approach better identifies the depositional areas such as alluvial fans and deltas with high SOC storage. These areas are also the key areas of deep carbon storage, which contribute with an additional 2.4 kg C $m^{-2}$ in the 1–3 m depth interval to the total SOC storage in Zackenberg (Figure 12).

The results emphasize the importance of geomorphology, in particular aggrading landforms, rather than land cover, when estimating SOC storage in mountain permafrost environments. However, since geomorphological maps are rarely available in the circumpolar areas, the LCC is still one of the few methods which allow producing SOC maps on landscape and regional scales.

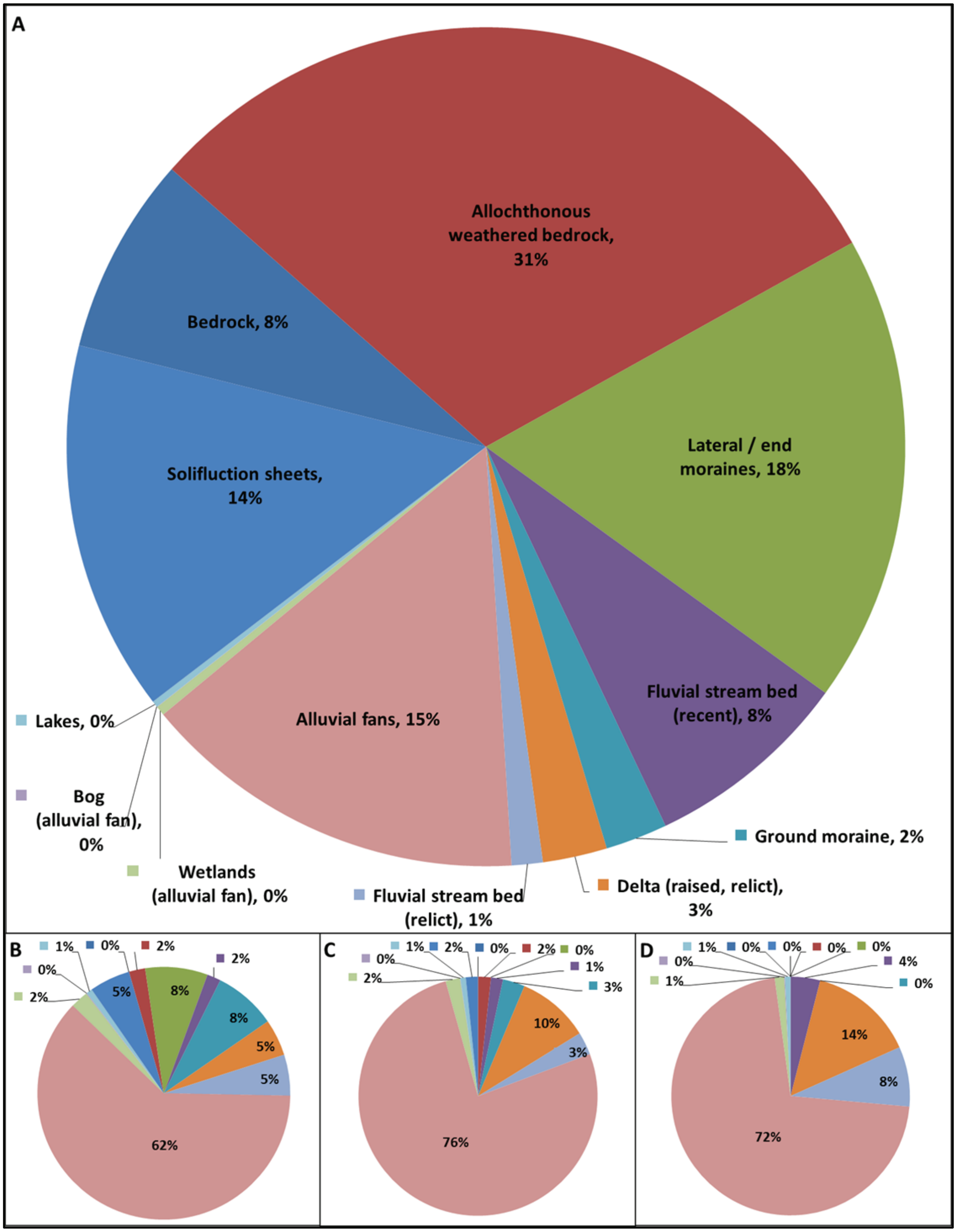



Figure 12. Proportional contribution of each landform to: A) Areal coverage of the total study area; B) total SOC storage for 0–100 cm; C) total SOC storage for 100–200 cm; and D) total SOC storage for 200–300 cm. Landform and colors from chart A apply also to charts B-D.

### 3.4 Paper IV

Palmtag, J. and Kuhry, P. Grain size controls on cryoturbation and soil organic carbon density in permafrost affected soils. Manuscript.

Paper IV is a meta-analysis of soil texture based on pedons collected from five different study areas within the continuous permafrost zone. The selected pedons and soil samples can be considered approximately representative for the top 1 m of mineral upland soils in four Russian lowland study areas (Shalaurovo and Cherskiy, NE Siberia; Logata and Ary-Mas, Taymyr Peninsula) and the lower central valley in the mountainous Zackenberg area (NE Greenland). The focus lies on how grain size influences cryoturbation and SOC storage in permafrost soils. The analysis is based on 165 mineral samples from 35 pedons.

The analysis has shown that differences in grain size spectra have a significant effect on cryoturbation, carbon concentrations and carbon densities. In the case of cryoturbation, which leads to a downward migration of organic-rich topsoil horizons into deeper layers resulting from freeze-thaw cycles, the process was most pronounced in soils with high coarse silt to very fine sand fractions. By subgrouping cryoturbation into C-enrichment classes from CT-CE3 (high), CT-CE2 (medium) to CT-CE1 (low) and no CE (none to negligible), we observe a higher level of C-enrichment in samples with high coarse silt and very fine sand fractions, while we have a reversed trend with the clay and very fine silt fractions (Figure 13). We hypothesize that the finer grain size fractions, with a reduced C-enrichment through cryoturbation, have stronger cohesion that reduce the mixing of horizons in the soil.

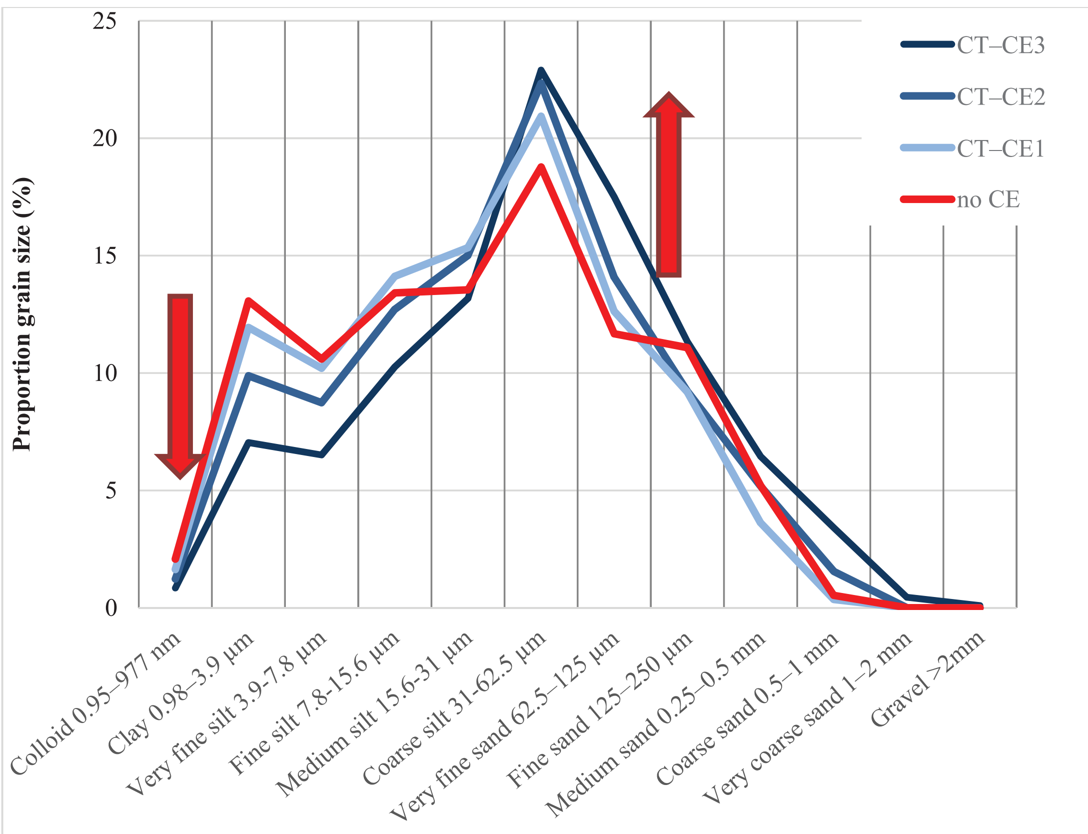



Fig. 13. Mean proportion (%) of grain sizes in all profiles and mineral subsoil samples from the four Russian lowland study areas, as a function of C-enrichment in cryoturbated pockets. 'CT-CE3' samples (dark blue line) show the highest C-enrichment; 'no CE' samples (red line) are not C-enriched. Red arrows indicate direction of increased C-enrichment.

However, when we exclude all samples affected by C-enrichment through cryoturbation we observe a different trend. The fine-grained soils with high clay to medium silt fractions store significantly more SOC in mineral subsoil than coarser textured soils. In these soils, finer grained textures provide a physical protection by coating the organic matter, while they also promote the formation of organo-mineral chemical bonds. Both these processes better protect SOM from decomposition.

Based on our results we can conclude that soil texture has an important effect on cryoturbation and carbon concentrations in permafrost affected soils. This outcome can be used when implemented in e.g. the Northern Circumpolar Soil Carbon Database (NCSCD) to characterise areas not only by soil types but also by their dominant soil texture, which would allow to adjust SOC concentration and C-enrichment values through cryoturbation.

# 4. Discussion

## 4.1 Storage and landscape partitioning of soil organic carbon

The main objective of my research was to estimate the total SOC storage, landscape distribution and detailed soil horizon partitioning in contrasting environments of the continuous permafrost zone. In paper I the research question was addressing SOC and aboveground phytomass carbon (PhC) storage variation on a regional scale. The study area consists of two lowland sites in Taymyr Peninsula located only 150 km apart. The results showed substantial mean SOC differences of c. 40% in the top 1 m between the two study sites, mainly due to the difference in soil texture. The mean SOC 0–100 cm content in the sandy-loam soils of Ary-Mas was 14.8 kg C $m^{-2}$, in comparison to 20.8 kg C $m^{-2}$ in the silty clay loam soils of Logata. On average, from all mineral soil profiles (organic layer, C-enriched cryoturbated pockets and mineral subsoil samples), the %C in Logata samples was about twice as high as in Ary-Mas. Results from radiocarbon dating indicated that Logata site soils are younger with on average higher C/N ratios. Additionally, both sites consisted of three geomorphological units (recent floodplains, pre-recent floodplains and uplands) with great differences in aerial coverage and SOC storage ranging from 3.4 kg $m^{-2}$ in recent floodplains to 25.5 kg $m^{-2}$ in uplands, both in Logata. These distinct results show the importance of soil texture (see also Gentsch et al., 2015), landforms (recent, pre-recent floodplains and uplands) and their age even on a regional scale, which emphasises the need of detailed field sites. Besides SOC content, another key finding was the contribution of aboveground phytomass to the total ecosystem stock, which was only 2% and thus almost negligible. With increased warming we can expect shifts in biome distribution, and increased phytomass and plant productivity (Natali et al., 2012). However, this increased carbon uptake is not likely to compensate for the carbon losses from thawing permafrost on decadal and longer timescales (e.g. Schuur et al., 2009).

In paper II we described and compared SOC quantity and SOM characteristics from two topographically very different regions, a mountainous high-arctic study area in NE Greenland vs a lowland region in NE Siberia with two study areas (Shalaurovo and Cherskiy). The mean SOC estimates for the top 1 m showed major differences between these two regions ranging from 8.3 to 30.0 kg C $m^{-2}$, stretching from 0 to 80 kg C $m^{-2}$ in individual pedons. The large variability can be mainly explained by the fact that c. 60% of the mountainous Zackenberg area is located at higher elevation with mostly barren ground. Another factor responsible for the great SOC variation are burial mechanisms. In case of Zackenberg, slope processes predominate in the area by gradually burying C-enriched top soil material into deeper layers which therefore were exposed to aerobic decomposition over long periods of time. In the four Russian study areas, cryoturbation was the dominant burial mechanism by rapidly mixing relatively fresh organic-rich topsoil horizons into deeper layers. The results from these different burial processes are reflected in contrasting C/N patterns. While in Zackenberg the C/N ratios from buried material shows no difference to adjacent mineral subsoil material, in Shalaurovo and Cherskiy the C/N ratios from cryoturbated pockets in comparison to adjacent mineral subsoil material were significantly higher indicating a lower level of SOM decomposition (Fig. 14). Therefore, this study highlights the importance of topographic and geomorphic settings as crucial factors when assessing the SOC quantity and SOM quality in such diverging environments.

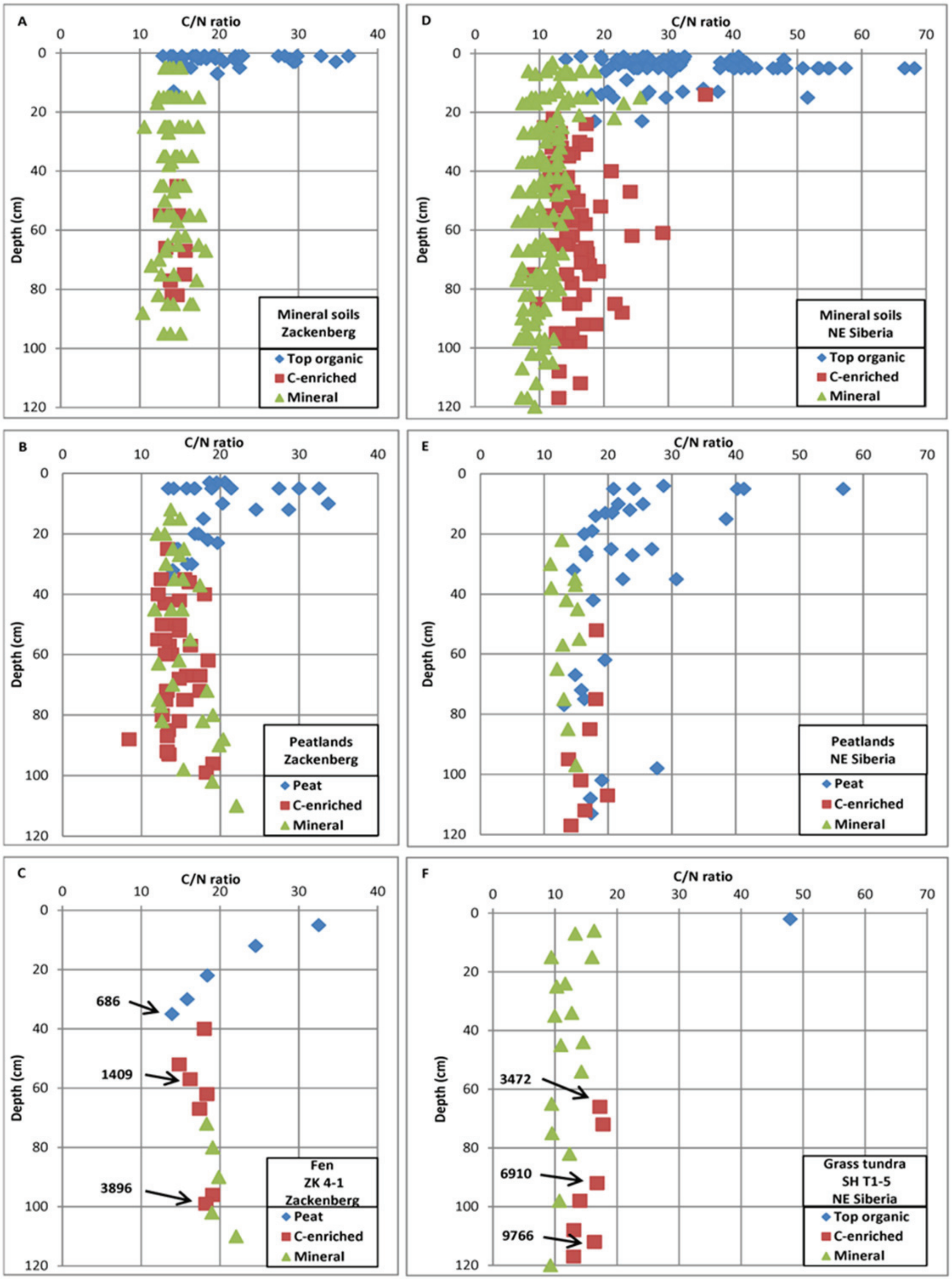



Figure 14. (A–F) Carbon to nitrogen (C/N) weight ratios subdivided into top organic/peat layer, C-enriched materials buried in mineral subsoil, and mineral subsoil for mineral soils, peatland soils, and selected profiles from NE Greenland and NE Siberia. Ages in cal yr BP are shown for a fen profile in Zackenberg and for a grass tundra profile in Shalaurovo (Palmtag et al., 2015).

In paper III we presented new improved SOC 0–100 cm estimates for the mountainous Zackenberg study area, based on geomorphological landform upscaling linked to our SOC values obtained from *in situ* sampling. In addition, this paper provided first SOC stocks for deeper deposits down to 3 m depth. The new mean SOC storage estimate was reduced compared to the original land cover upscaling by 42% from 8.3 to 4.8 kg $m^{-2}$ in the top 1 m, with an additional 2.4 kg C $m^{-2}$ stored in the 1–3 m depth interval. We ascribed the substantial decrease of SOC 0–100 cm to an aerial overestimate of SOC-rich vegetated classes (c. 40% of the study area) in the original LCC approach. The geomorphological upscaling allowed a much better mapping of SOC hotspots in the landscape by properly identifying areas of accumulation in alluvial fans and deltas (c. 22% of the study area). This study emphasizes the shortcomings of a LCC approach for SOC upscaling, particularly in mountainous settings. However, a limitation remains that geomorphological maps are rarely available in the northern circumpolar areas.

In papers I, II and III we presented detailed SOC estimates from five different study areas in under-sampled regions with continuous permafrost. With estimates between 4.8 and 30.0 kg C $m^{-2}$ calculated to 1 m depth, our results are in accordance with other local studies (Kuhry et al., 2002; Hugelius et al., 2010; Mergelov and Targulian, 2011; Zubrzycki et al., 2013; Gentsch et al., 2015) but lower than reported estimates for Alaska and the Canadian Arctic (Michaelson et al., 1996; Ping et al., 2008; Tarnocai et al., 2009). The SOC estimates in the NCSCD are higher than our mean values for the respective study areas (Table 2).

Table 2: Comparison of NCSCD v1 (Tarnocai et al., 2009), v2.2. (http://bolin.su.se/data/ncscd/) and landscape-level SOC 0–100 cm inventories for five study areas.

| Study areas | Mean SOC storage estimates (kg C $m^{-2}$) | | |
|---|---|---|---|
| | NCSCD v1 | NCSCD v2.2 | Our studies |
| Zackenberg | 24.2 | 17.8 | 4.8 |
| Shalaurovo | 38.4 | 38.4 | 30.0 |
| Cherskiy | 38.4 | 38.4 | 20.3 |
| Ary-Mas | 30.0 | 30.0 | 14.8 |
| Logata | 35.0 | 35.0 | 20.8 |

This is because the NCSCD is overestimating the proportion of SOC-rich soil types such as Turbels and Histels in comparison to our own results. Furthermore, the mean SOC stock in the NCSCD for uplands is based on mean SOC stocks for these soil types for all of Russia. The NCSCD reports 30.0–35.0 kg C $m^{-2}$ in the Taymyr Peninsula study region. Our mean values for uplands range between 17.5 and 25.5 kg C $m^{-2}$, based on local sampling at 24 and 18 sites in Ary-Mas and Logata, respectively. For the Shalaurovo and Cherskiy area, the NCSCD estimate is 38.4 kg C $m^{-2}$ compared to our mean values of 30 and 20.3 kg C $m^{-2}$, respectively. Whereas for the Zackenberg area our mean SOC value is only 4.8 kg C $m^{-2}$ in comparison to 17.8 kg C $m^{-2}$ in the updated version from the NCSCD (v2.2). On the other hand, SOC values for the Tulemalu study area in the continuous permafrost zone of Central Canada were lower in the NCSCD than in the landscape level inventory (21.4 vs 33.8 kg C $m^{-2}$, respectively), because of an underestimate in the coverage of Histels (Kuhry et al., 2010). Therefore, to reduce uncertainty and increase our understanding on key factors influencing the variability in SOC stocks, additional regional and landscape-level field studies, especially in under-sampled permafrost regions, are needed. The SOC inventory data from Paper II has already become part of the Northern Circumpolar Soil Carbon Database (v2.2 is currently available online at http://bolin.su.se/data/ncscd/ ; doi:10.5879/ECDS/00000002).

## 4.2 Grainsize distribution and cryoturbation

Cryoturbation is a major soil process for burying C-enriched material into deeper layers (Bockheim and Tarnocai, 1998; Kaiser et al., 2007). Warped, irregular and involuted horizons (see Fig. 4A/B) were observed at all five study sites, in both the active layer and the upper permafrost layer. In case of the four Siberian lowland sites, as much as 30% of total landscape SOC to 1 m depth was stored in C-enriched cryoturbated pockets, which is in accordance to other lowland studies (e.g. Hugelius et al., 2010). This proportion is even higher if considering only mineral upland soils (excluding wetlands, floodplains, etc.). In the top 1 m of upland soils, the contribution of the C-enriched cryoturbated pockets could be >50% of the total stored SOC. Radiocarbon dating of C-enriched pockets in the Russian lowland sites indicate that cryoturbation has occurred since at least 8000 to 10 000 years. In Zackenberg, cryoturbation was mostly restricted to flat, stable surfaces in the central valley. Slope processes were the main mechanism for burying C-enriched layers in alluvial fan deposits in foothill areas.

Soil profiles affected by C-enrichment through cryoturbation were typically characterized by relatively high coarse silt to very fine sand fractions (Fig. 15). All mineral uplands soils in Shalaurovo (NE Siberia) had C-enriched pockets and displayed these characteristics. On the other hand, soil profiles not affected by C-enrichment through cryoturbation had either a higher contribution of finer (clay to medium silt) fractions as in Logata (Taymyr Peninsula) or coarser (fine to coarse sand) fractions as in Ary-Mas (Taymyr Peninsula).

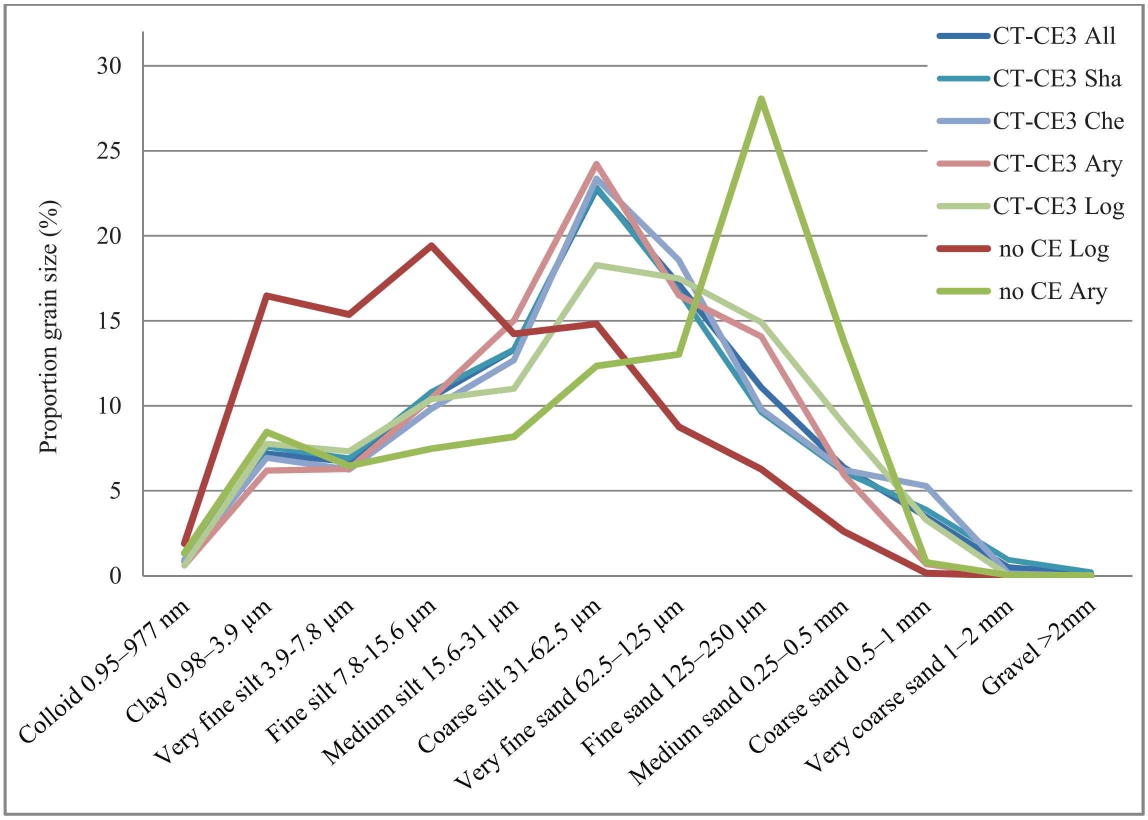



Figure 15. Mean grain size proportions (%) for all C-enriched cryoturbated pockets in mineral upland soils (highest level CT3) for all four Russian lowland study areas and for each of the four Russian lowland study areas separately (highest level CT3) vs mean grain size of non C-enriched samples in profiles not visibly affected by cryoturbation in Logata and Ary-Mas.

## 5. Conclusions

This thesis provides mean SOC 0–100 cm storage estimates for five new study areas within the continuous permafrost zone. Our results from Russian lowland areas (14.8–30.0 kg C $m^{-2}$) are comparable to other local studies from northern Russia, but are considerably lower than most results reported from Alaska and Canada. Our mean SOC storage estimates are also lower than those reported for the same Russian areas in the Northern Circumpolar Soil Carbon Database.

Differences in SOC storage to 1 m depth on a pedon base varied between 0 kg C $m^{-2}$ on exposed bedrock in a mountainous site (Zackenberg, NE Greenland) to 80 kg C $m^{-2}$ in Russian lowland bogs. This fact makes some land cover classes, e.g. wetlands, critically important especially when they occupy larger areas. Our research has shown that SOC storage in permafrost soils has a very large variability even on a local scale, and emphasizes the need to consider not only different land cover classes, but also topography, geomorphology, soil texture, soil moisture content and other edaphic factors. In paper I we showed that the mean SOC storage between Ary-Mas and Logata differed by c. 40% mainly because of soil texture. While in case of Zackenberg (paper III), the mean SOC storage was reduced by c. 40% by using geomorphology instead of land cover upscaling. In this mountainous environment, geomorphology became even more important to identify the hotspots of deep carbon storage (alluvial fans and deltas).

Cryoturbation was one of the main soil forming processes and observed at all our study sites. This process has buried large amounts of relatively fresh SOM in permafrost soils. In case of the four Russian lowland sites, it was the predominant process and storing roughly 30% of the total landscape SOC in C-enriched cryoturbated pockets. In Zackenberg, we observed that slope processes were the main mechanisms in burying C-rich surface material into deeper layers, with cryoturbation restricted to the lower central valley only. Our geochemical results indicate that C-enriched cryoturbated pockets contain relatively low decomposed SOM material due to very rapid burial. In contrast, top soil organic matter incorporated into alluvial fan deposits was more decomposed because of only gradual burial. The question remains if with increased temperatures due to climate warming, cryoturbation will increase the burial of SOM (Bockheim et al., 2007) or if active layer thickening will lead to increased decomposition rates of buried layers.

Fine-grained soils have higher SOC background values in mineral subsoil. Our results show that the clay to medium silt fractions are all positively correlated to %C and C density (kg C $m^{-3}$) values in mineral subsoil samples without any signs of C-enrichment through cryoturbation. Apparently these soil textures are more conducive to the formation of organo-mineral associations leading to an increased storage of SOC. On the other hand, the coarse silt and very fine sand fractions are positively correlated to C-enrichment through cryoturbation. The coarse silt to clay ratio of mineral upland soils shows a very strong correlation to C-enrichment within and across all investigated study areas.

To conclude, all our findings highlight the importance of detailed field studies that are crucial to capture the SOC variability at local, landscape, regional and circumpolar scales. Detailed information on SOC quantity and SOM quality across spatial scales and within soil profiles are essential for benchmarking of Earth System Models and reduce uncertainties in projections of the permafrost carbon-climate feedback under conditions of global warming.

# 6. Perspectives on future research

The focus of the thesis was to gain detailed knowledge about SOC storage and partitioning in remote areas underlain by continuous permafrost. Obtained results highlighted the importance of geomorphology, land cover, soil texture, and other factors. Our results on mean SOC storage were much lower than previous regional and circumpolar estimates. Therefore, the only way to reduce uncertainties on a circumpolar scale, which is extremely important as such data is used for benchmarking in Earth System models to assess the permafrost carbon-climate feedback on global warming, is to increase the number of detailed regional field studies (Papers I, II, III) emphasizing especially under-represented areas such as the High Arctic, mountain permafrost and Russia.

The next challenge is to improve circumpolar products like the NCSCD:

- Our results from paper I have shown that geomorphological units such as uplands, recent and pre-recent floodplains in lowland settings had substantial mean SOC differences. Such geomorphological unit partitioning on a circumpolar scale, which could be done based on LCC from low resolution Landsat satellite imagery, would improve the NCSCD estimates considerably.
- Findings from paper III have pointed out the importance of geomorphology regarding SOC storage in mountainous regions. In Zackenberg, alluvial fans which occupy only 15% of the area store >60% of the total SOC to 1 m depth. This proportion of the total SOC storage even increases with depth (1–3 m stocks). By incorporating digital elevation models (DEM) data, which is nowadays available on a circumpolar scale, such SOC hotspots can be identified remotely and taken into account when calculating the SOC pools.
- The third important factor controlling the SOC storage and favouring burial processes is soil texture. In paper IV we see clear correlations between very fine grained sediments and higher SOC storage. Furthermore, burial processes such as cryoturbation are enhanced by larger grain sizes (coarse silt to very fine sand). Much soil texture data on larger scales is available from digital soil and lithology maps and can be used to infer differences in SOC burial and enrichment at regional scales.

As a result, by adding additional layers of data (LCC, DEM, soil texture) to the NCSCD, we could reduce considerably uncertainties and improve estimates.

However, with respect to the permafrost carbon-climate feedback the quality and lability of SOC is as important as the quantity regarding the microbial decomposition of permafrost SOM and release of greenhouse gases under future global warming. Paper I and II has shown that a substantial amount of fresh undecomposed organic material is located in cryoturbated C-enriched pockets. But insufficient knowledge is available about SOM vulnerability and degradation under permafrost thawing. This should be one of the focus areas for future work.

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