High-resolution mapping of soil organic carbon storage and soil properties in Siberian periglacial terrain

Matthias B Siewert
High-resolution mapping of soil organic carbon storage and soil properties in Siberian periglacial terrain

Abstract

In the past years considerable attention has been given to soil organic carbon (SOC) stored in permafrost-affected soils in periglacial terrain. Studies have shown that these soils store around half the global SOC pool, making them a key component of the global carbon cycle. Much of the SOC presently stored in these soils has accumulated since the Pleistocene and is protected from decomposition and erosion by low temperatures close to or below the freezing point. This makes it vulnerable to remobilization under a warming climate. This thesis provides new data on SOC storage in three study areas in Siberian periglacial terrain. A high-resolution land cover classification (LCC) for each study area is used to perform detailed vertical and spatial partitioning of SOC. The results show that the vast majority (>86%) of the ecosystem carbon is stored in the top meter of soil. Low relative storage of carbon in plant phytomass indicates limited uptake potential by vegetation and emphasises the vulnerability of the SOC pool to geomorphic changes. Peat formation as well as cryoturbation are identified as the two main pedogenic processes leading to accumulation of SOC. Presence or absence of ice-rich Yedoma deposits determine soil formation and SOC storage at landscape scale. At local scale, periglacial landforms dominate SOC allocation in the tundra, while forest ecosystem dynamics and catenary position control SOC storage in the taiga. A large diversity of soil types is found in these environments and soil properties within pedons can be highly variable with depth. High-resolution satellite imagery allows upscaling of the SOC storage at unprecedented detail, but replication of soil pedons is a limiting factor for mapping of SOC in remote periglacial regions. Future research must look beyond traditional LCC approaches and investigate additional data-sources such as digital elevation models. The concept of state factors of soil formation is advocated as a framework to investigate present day and future SOC allocation in periglacial terrain.
This licentiate thesis includes a general summary and two papers.

**Paper I:**
Comparing carbon storage of Siberian tundra and taiga permafrost ecosystems at very high spatial resolution. *Journal of Geophysical Research: Biogeosciences*

**Paper II:**
Siewert, M. B. & Hugelius, G., Landscape controls on soils and soil organic carbon storage in the Lena River Delta. (Manuscript)

**Author contribution of paper I:**
Fieldwork in Kytalyk was carried out by me, Gustaf Hugelius, Jessica Hanisch, Niels Weiss, Juri Palmtag and Daiga Smeke. Fieldwork in Spasskaya Pad was carried out by me, Jessica Hanisch, Niels Weiss, Daiga Smeke and Peter Kuhry. The laboratory analyses were carried out by Jessica Hanisch, me and Niels Weiss. I did all the writing. I did all the remote sensing analysis, the statistical analyses and prepared all figures. The co-authors helped with the interpretation of the results and with the writing.

**Author contribution of paper II:**
Fieldwork in the Lena River Delta was carried out by me, Gustaf Hugelius, Johannes Petrone, Samuelle Faucherre and Christian Juncker Jørgensen. The chemical analyses and organization of the data was done by me and Johannes Petrone. I did all the remote sensing analysis, the statistical analyses and prepared all figures. Gustaf Hugelius participated in the interpretation of the results and helped with the writing.
High-resolution mapping of soil organic carbon storage and soil properties in Siberian periglacial terrain

1. Introduction

The current global warming trend has influence on permafrost ecosystems that may lead to changes relevant to the global carbon (C) cycle. Therefore, integrated regional studies are recommended to analyze carbon dynamics and associated processes in high latitude terrestrial ecosystems (McGuire et al., 2009). Soil organic matter (SOM) is an important pool of C in these dynamics. SOM consists of partly decomposed flora and fauna in soil and is rich in soil organic carbon (SOC). In the Arctic and Subarctic, SOC is often preserved by permanently frozen ground called permafrost. Permafrost is defined as ground material at or below 0°C for two or more consecutive years (Van Everdingen, 1998). The northern circumpolar permafrost region covers an area of $18,782 \times 10^3$ km² and is subdivided into four zones, in which permafrost occurrence is continuous ($\geq$90 to 100%), discontinuous ($\geq$50 to <90%), sporadic ($\geq$10 to <50%) or restricted to isolated patches (0 to <10%) (Brown et al., 1997). This thermal regime promotes a set of pedogenic processes and periglacial landforms, like ice-wedge polygons (Figure 1) and non-sorted circles, that are unique to this environment and favored the build up of large stocks of SOC during the Quaternary (Ping et al., 2015). The first attempt to quantify the global SOC pool for individual ecosystems was provided by Schlesinger (1977). His combined estimate of SOC storage for “Tundra and Alpine” (173 Pg), “Boreal forest”(179 Pg) and “Swamp and marsh”(137 Pg) of a total 489 Pg covers an area that probably corresponds best to the outline of the northern circumpolar permafrost zone. The permafrost carbon pool has only received considerable attention, after a review by Gruber et al.

![Figure 1: Ice-wedge polygon landscape in a floodplain environment near Chokurdakh, Siberia. The size of each polygon feature is approximately 7-15m in diameter.](image)
(2004) identified permafrost as one of the key carbon pools in the global carbon cycle. The authors concluded that this SOC is presently locked in frozen state, but may be vulnerable to thaw and remobilization due to climate change. At the time permafrost carbon pool was estimated to 400 Pg (Gruber et al., 2004). Consequently, both “permafrost and tundra loss” and “boreal forest dieback” (or biome switch) have been identified as two ecosystem adjustments to climate change that are potential tipping elements in the earth's climate system. A tipping point refers here to a critical threshold at which small perturbations can alter the state of the climate system and its future development leading to - potentially abrupt - climatic changes (Lenton et al., 2008). The vulnerability of the permafrost carbon pool to climate change and its remobilization were thereupon assessed. Widespread permafrost degradation, which may occur both gradually and catastrophically, will expose large amounts of previously frozen SOC and make it available to microbial decomposition. Depending on hydrological conditions this can result in the emission of carbon dioxide or methane to the atmosphere. At the same time, ecosystem dynamics may adjust to a warming climate and lock this carbon as plant phytomass. However, it was concluded that the net effect will be a substantial carbon release at decadal to century timescale and a positive feedback towards a warmer climate (Schuur et al., 2008). To improve carbon pool estimates for the northern circumpolar permafrost region, as defined by Brown et al. (1997), the Northern Circumpolar Soil Carbon Database (NCSCD, Hugelius et al., 2013) was compiled. It is a database of soil cover and carbon rich sediments of this region. Using this product, the permafrost carbon pool has been estimated to 1672 Pg. The substantial increase over earlier estimates mainly stems from the inclusion of previously unrecognized deeper soil 100-300 cm depth (528 Pg), deeper Yedoma deposits (407 Pg) and deltaic deposits (241 Pg) (Tarnocai et al., 2009). Recently, the global SOC mass within the top 1 m of soil has been estimated to 1325 Pg using an updated version of the Harmonized World Soil Database (HWSD). This estimate combines different sources including the 496 Pg of SOC estimated by Tarnocai et al. (2009). Permafrost affected soils thus represent around 37% of the global SOC within this measuring interval. The total mass of SOC including soils deeper than 1 m is estimated to 3000 Pg of which around half is located in the permafrost regions (Köchy et al., 2015). The latest estimate of SOC in the northern circumpolar permafrost region by Hugelius et al. (2014) estimates the SOC pool in the top 1 m to 472±27 Pg and the total SOC pool in the region to 1307 Pg with an uncertainty range of ~1140–1476 Pg. While this estimate is not substantially different to the estimate by Tarnocai et al. (2009), the study also concludes that there remains a general shortage of soil pedon data to quantify the SOC pool of this region and that much of the available data is regionally clustered.

With around one decade of greater attention, our knowledge on the permafrost carbon feedback has significantly improved. A recent review by Schuur et al. (2015) confirms many of the above findings. Climate warming in the high latitudes is indeed likely to cause increased greenhouse gas emissions from the permafrost carbon pool, which in turn will be a positive feedback to climate change. Environmental changes are likely to accelerate microbial breakdown of SOC and release the greenhouse gases carbon dioxide and methane. At the same time, it is acknowledged that the quantity per time of this release remains uncertain, but will likely be more gradual and prolonged than previously thought. The recommendations include to explicitly define the vertical distribution
of SOC in permafrost soils in models and to further improve the amount of data in remote areas, including central Siberia, and for depths greater than 1 m.

2. Objectives of the thesis

The quantification of SOC stocks in the permafrost affected regions has seen considerable progress in the past decade. Nevertheless, more soil pedons and more replicates of important ecosystems are needed. The first objective of this thesis is to contribute new data and insights to ongoing research efforts to better constrain the pool of SOC in Siberia. A particular emphasis and second objective is to investigate tools and methods to quantify SOC in periglacial terrain. This includes the use of very high spatial resolution satellite imagery and alternate land cover classification (LCC) approaches. This relates to the third objective, which is to analyze patterns of SOC distribution across different environmental gradients. These environmental gradients include continental scale geographical gradients to site scale differences in SOC allocation.

Figure 2 Circumpolar map of the SOC storage in the top meter (data from Hugelius et. al 2014). The study areas of this thesis are marked by a blue point.
3. Study areas

Fieldwork has been carried out in three study areas located in Eastern Siberia (Figure 2) and are referred to as: Kytalyk, Spasskaya Pad/Neleger and the Lena River Delta. All three areas are located within the Sakha Republic (Yakutia) in Russia in the zone of continuous permafrost (Brown et al., 1997). While Spasskaya Pad/Neleger has a hyper-continental climate supporting a taiga forest ecosystem, both, Kytalyk and the Lena River Delta, have a more maritime climate, are located North of the treeline and support a lowland tundra ecosystem. In all three study areas ice-rich Yedoma type sediments are present. This set of properties makes them suitable study areas to derive conclusions that should be applicable to large parts of Siberia and in part also for other regions with continuous permafrost.

4. Background

4.1. Beringia

Siberia represents globally the largest region affected by permafrost (Figure 2), but has also been pointed out as a significant regional data gap for estimates of SOC (Hugelius et al., 2014; Zubrzycki et al., 2014). To understand present day SOC storage and potential future dynamics of this carbon pool, the long-term history of Siberia, back to the Pleistocene, needs to be taken into account.

During the Pleistocene, a large area in Siberia, the Bering Strait and Alaska experienced ice-free conditions, while ice-sheets covered much of Europe and North America. This unglaciated area is called Beringia and was first described by Hultén (1937). The present day usage of the term Beringia refers to a region stretching approximately from the Taymyr Peninsula in western Siberia to the Yukon Territory in western Canada. During the Late Pleistocene the area was connected by a land bridge across the Bering Strait as the sea level was repeatedly lower than today, exposing extensive areas of the continental shelf (Schirrmeister et al., 2012). Much of Beringia has experienced periglacial conditions at least >50 ka BP years, which has not only promoted a unified cold-adapted flora and fauna, but also a unique sediment suite (Schirrmeister et al., 2012). Intense periglacial weathering generated fine-grained sediments that were deposited in accumulation plains to sometimes over 50 m thickness (Schirrmeister et al., 2011, 2012). These were incorporated into syngenetically forming permafrost. In Russia these sediments are commonly called Yedoma or ice-complex due to the high ice-content that can be up to 80% of the volume (Figure 3; Schirrmeister et al., 2012). A typical feature of this ice-complex are ice-wedges of several meter thickness that are arranged in a polygonal pattern (when viewed from above; Figure 5). These areas have been partly eroded, but remnants are still a common occurrence in Arctic and Subarctic Siberia, Alaska and western Canada (Schirrmeister et al., 2012). They provide a legacy of thermally erodible ice-rich sediments that locally dominate the landscape scale geomorphological setting and soil formation.
4.2. Permafrost affected soils

The evolution of ecosystems and soils over time is variable for different landscapes. Soils along environmental gradients are commonly seen as a function of time and variation of different state factors of soil formation. The idea of such a relationship has first been formulated by Dokuchaev (1898, in Jenny, 1980) and later on developed particularly by Hans Jenny (1941, 1980). Jenny 1941 described that any soil property (S) is a function of different state factors which are the external climate (cl), the biotic potential (o), the topography and water table (r), the initial state and parent material (p), time (t) and additional factors (…) that can be unique to any particular situation:

\[ S = f(cl, o, r, p, t, ...) \]

Jenny also recognized that SOC storage is related to these state factors (Jenny, 1980). Ping (2013) describes how these individual soil-forming factors are altered in periglacial landscapes affected by permafrost. The following discussion adapts the concept to the specific case of Siberian periglacial terrain where the study areas of this thesis are located.

Figure 3: Exposure of Yedoma deposits near Kytalyk. Massive dirty to almost pure ice is interrupted by organic rich sediments that have been deposited during the Pleistocene. At the top of the surface Holocene soils and ice-wedges have formed. Approximately 16 % of the area is covered by remnants of a former Yedoma surface which has been eroded by various thermokarst processes. The inlet shows the landscape expression of the remnants which elevate ~10-30 m over the surrounding area.
The cold climate leads to the particular thermal regime causing permafrost. This causes formation of cryostructures and cryoturbation, a thermal induced turbic process transferring soil material, sometimes entire organic soil horizons, within the pedon (Figure 4, Ping et al., 2008). The cold soil thermal regime also reduces organic matter decomposition and favors its accumulation and peatland formation is a common process. Periglacial landscapes include lowlands as well as alpine environments with a wide range of parent materials. The texture of the parent material influences the intensity of cryoturbation (Ping, 2013). Afore-mentioned Yedoma deposits, that commonly have a fine-grained texture, can be found as relief forming remnants throughout much of Siberia. Many of these have been affected by landscape scale thermokarst features, where much of the ground-ice has thawed out (Figure 5, Schirrmeister et al. 2012). Permafrost environments also feature distinct landforms that are relevant to carbon accumulation. Repeated strong gradients in temperature and hydrology force the soil to cryoturbation, which is then expressed in patterned ground. This is considered a manifestation of self-organization (Walker et al., 2008). Thermal-cracking promotes the formation of wedge-like ice-bodies that form self-organized polygonal patterns that can be seen from above (Figure 1). Pleistocene aged ice-wedges can be several meters wide (Schirrmeister et al., 2012). Degradation of Yedoma deposits often results in formation of thaw lakes, which when drained can form kilometer scale drained thermokarst (thaw) lake basins (DTLB) providing particular ecosystem environments (Grosse et al., 2013). Vegetation and surface organic matter accumulation are important controls of permafrost formation and fire is part of natural ecosystems dynamics in the taiga/boreal forest. These ecosystem dynamics are complex. Vegetation can for example be the factor that preserves permafrost from degradation (Shur and Jorgenson, 2007). Lastly, the temporal evolution has not been the same for all Arctic soils. While some areas, like northern Fennoscandia, have been repeatedly glaciated and partly stripped of their near surface soils during the Quaternary, much of Beringia has experienced periglacial conditions for over one hundred thousand years (Hultén, 1937; Schirrmeister et al., 2012). These factors condition SOC
storage in different ways (Ping, 2013) and this thesis will try to give insights into some of these aspects.

4.3. How to quantify SOC

The relevance of the permafrost carbon pool highlights its quantification and with this a methodological question of how to quantify this carbon pool. SOC stocks at landscape level are commonly estimated by thematic upscaling. SOC stocks from soil pedons collected in the field are averaged for separate classes. These averages are linked to the areal coverage of the respective class derived from a soil map or a LCC.

The NCSCD, which has been used for the estimates provided by Tarnocai et al. (2009) and Hugelius et al. (2014), is a compiled and homogenized soil database that works with discrete polygons for individual soil types. The map is a circumpolar product and individual polygons commonly have a scale of several kilometers. The detail of individual areas also depends on the source material and is not uniform (Hugelius et al., 2013). At local scale soil maps are rare, for example Kuhry et al. (2002) mapped SOC storage based on a soil map of the Usa Basin, but often these maps do not exist. Periglacial landscapes can be very heterogeneous at local scale, with very patchy land cover changing at meter scale (Virtanen and Ek, 2014). This heterogeneity applies to

Figure 5: Illustration of the periglacial landscape in Kytalyk. The left image shows the landscape from a Landsat 5 image. Large kilometer scale thermokarst lakes dominate the landscape in the North. This area is divided from the southern, Yedoma plateau dominated region, by a floodplain. The middle image shows meso-scale zoom a GeoEye-1 image of the study area to the bottom right a Yedoma remnant is visible, undercut by an old river arm in the South and by a thermokarst lake that has drained in the North. The right bottom image shows the same Yedoma plateau. The upper right image shows an area within the second generation of the drained thermokarst lake. This area is dominated by ice-wedge polygons.
landforms, vegetation and soils and manual mapping is unrealistic. LCCs based on remote sensing products are a viable alternative and are a commonly used tool to quantify ecosystem properties. A good example is the CORINE Land Cover map of Europe initiated by the European commission (Bossard et al., 2000). Several authors have used LCCs to upscale soil pedon data to landscape scale in permafrost affected environments (Kuhry et al., 2002; Hugelius et al., 2011; Zubrzycki et al., 2013). The added value of using high-resolution land cover maps for upscaling of SOC has been explored by Hugelius et al. (2011), who showed that the higher resolution was necessary to locate hot spots of SOC storage in a tundra environment.

5. Methods

5.1. Field methods

Soils are sampled in the field according to a transect sampling scheme with 4 to 10 sampling sites per transect. These equidistant (100 to 150 m sampling distance) transects are laid out to represent all major land cover types and/or geomorphological units found in a study area. In some cases, few additional field sites were sampled to complement particular land cover classes otherwise missed. This sampling scheme represents a semi-random sampling approach that compromises efficiency in a limited time-frame during a field campaign in difficult terrain.

At each sampling site a soil pit was dug to the bottom of the active-layer (whenever possible; Figure 6). The frozen permafrost was sampled by hammering a steel pipe in the ground at the bottom of the soil pit. The surface organic layer was sampled completely by cutting out blocks of known volume. In Kytalyk and Spasskaya Pad/Neleger, three samples of the organic layer were collected to replicate its natural variability, one from the main soil pit and two from a randomized position within 2 m distance. The mineral active layer was sampled using a fixed volume cylinder (60 or 100 cm$^3$) in 5 cm depth increments. In the Lena Delta a detailed sketch of the soil pit was made and the active layer was sampled per soil horizon. The surface area of each soil horizon within the soil pit was derived from a perspective-corrected photograph. The permafrost was sampled in 10 cm increments at all sites. In addition, a general site description was made and metadata was collected describing different factors such as vegetation, geomorphology, topography and water drainage. Vegetation was documented in terms of coverage by plant functional type in a 1 × 1 m plot. Plant samples were taken to estimate phytomass carbon (PC). Soils were classified according to the US Soil Taxonomy system (Soil Survey Staff, 2014).
Figure 6: Sampling of permafrost affected soils. a) Organic rich and poorly consolidated sediments found in peatlands or lakes are often sampled using a fixed volume Russian peat corer. b) The permafrost is sampled by hammering a 4.2 cm Ø steel pipe into the ground. c) Samples of organic rich soil with massive ice lenses retrieved from the permafrost with a pipe. d) Open soil pit.
5.2. Soil laboratory methods

For all three field campaigns a total of 107 field sites have been sampled (Kytalyk: 24; Spasskaya Pad/Neleger: 33; Lena Delta: 50) with ~5-15 samples per field site. All samples were oven-dried at 75°C for 3 or more days. Dry Bulk density (g cm\(^{-3}\)) was calculated from the field volume and the dry soil mass. Loss on ignition analysis (LOI) was performed on each sample by drying a small sub-sample overnight at 105°C and then burning it at 550°C for 5 h (Heiri et al., 2001). A subset (ca. 15%) of all samples was submitted to a laboratory to measure the elemental carbon and nitrogen content in an Elemental Analyzer (Carlo Erba NC2500, at the Department of Geological Sciences, Stockholm University). From samples where both LOI and the elemental carbon content was known polynomial regressions were used to generate a pedo-transfer function to estimate SOC content for the samples where only LOI was known. The SOC storage in kg C m\(^{-2}\) per sample was calculated by multiplying the fraction of organic C, bulk density (g cm\(^{-3}\), BD) and depth interval (T), corrected for the fraction of coarse fragments (CF, \(>2\) mm diameter):

\[
SOC = (C \times BD \times (1 - CF) \times T) \times 10
\]

To cover all depth increments per study site, soil properties of unsampled depth increments were interpolated based on samples from above or below the interval with the help of field notes on soil horizons and property changes. The SOC storage was aggregated for each individual pedon and partitioned for several depth intervals. These include intervals of 0-30 cm, 0-100 cm and 0-200 cm (only for Spasskaya Pad/Neleger), the organic layer, the mineral layer, the active layer, the upper permafrost and cryoturbated soil layers (CT, only paper I). In paper II a set of soil properties (SOC, BD, C%, Water % and visible ice content) have been plotted for the depth interval of 0-100 cm with a resolution of 1 cm. This analysis aims to resolve the vertical variability of SOC within class averaged soil pedons.

5.3. Remote sensing methods

For each study area a LCC was created from very high-resolution multi-spectral satellite imagery (pixel sizes 2 to 6.5 m). For this, areas with known surface cover were marked as training areas on the imagery to classify the entire imagery. The classes in Kytalyk and Spasskaya Pad were chosen to represent land cover typical for ecological vegetation assemblages described in the field. In the Lena delta the classes were chosen to represent the range of land cover types observed within major geomorphological units. The accuracies of the resulting LCCs was measured using data from independent ground control points and expressed using the Kappa coefficient and the overall accuracy, two statistical measures commonly used in remote sensing (only paper I). For upscaling, the soil profiles were grouped using the same classes. From the area covered by each class and the SOC storage calculated from the soil pedons, the total carbon storage per class and the area weighted total landscape carbon storage was calculated.
5.4. Data processing and multivariate statistical analysis

For all advanced data calculations, the R statistical software was used (R Core Team, 2015). In paper 1, multivariate statistics were used to analyze patterns in vertical SOC and PC allocation at study site level and how these relate to LCC classes, geomorphological classes and other environmental variables. The specific method used was non-metric multidimensional scaling (NMDS). NMDS is a method for indirect gradient analysis recommended due to its robustness against artifacts. First, Gower's dissimilarity-metric was used to rank the individual soil pedons (Gower, 1971). NMDS then finds a position for the pedons in ordinate space in a defined number of dimensions by optimizing the agreement between the rank order distances and the dissimilarities (Henderson et al., 2008).
6. Results

6.1. Summary of the included papers

6.1.1. Paper I


In this study we estimate and analyze ecosystem carbon storage combined from SOC and PC in two study areas in E and NE Siberia using high resolution satellite imagery and multivariate ordination analysis. The study sites represent two contrasting continuous permafrost ecosystems. This includes one lowland tundra ecosystem, Kytalyk, situated in the Kolyma lowlands and one taiga forest ecosystem, Spasskaya Pad/Neleger, situated on the West bank of the Pleistocene terrace of Lena river near the city of Yakutsk. In each study area three transects were defined across different environmental gradients of the study area. Along these transects field sites were registered in fixed intervals of 100 or 150 m. In the tundra area, we sampled a total of 24 field sites and in the taiga study area a total of 33 field sites. At each individual site, we sampled the soil and vegetation plant functional types. In Kytalyk we aimed to sampled the soil down to 1 m depth, while in Spasskaya Pad/Neleger, where the active layer is typically deeper, we aimed to sample to 2 m depth. The SOC was partitioned into different depth intervals and different horizon types: 0-30 cm, 0-100 cm, 0-200 cm, the top organic layer, the mineral soil layer, active layer, permafrost layer and cryoturbated soil layers. For both areas very high resolution (2 × 2 m) satellite imagery was used to generate LCCs. The initial result of the LCC showed high noise levels that have been addressed applying post-processing filters (Figure 7). This improved the quality of the final product significantly (Figure 8). The LCCs reflect soil and vegetation classes that were recognized in the field and the sampling sites where grouped according to these same classes. The accuracy of these LCC products was assessed using a set of ground truthing points from the field. The landscape partitioning of SOC and the PC was performed by multiplying mean storage values per class by the respective areal coverage from the LCC. Non-Metric Multidimensional Scaling (NMDS) was used to analyze differences in ecosystem carbon storage between the individual field sites in ordinate
space and how they compare to a set of environmental variables. To enable this they are presented in groups according to their LCC class and also according to their geomorphological position.

In Kytalyk, three major geomorphological units can be distinguished, plateau forming Yedoma remnants, DTLBs and an active floodplain (Figure 8a, b). These are the major determining factors behind the environmental gradients observed in the field. The entire area was formerly covered by Pleistocene ice-rich Yedoma deposits. During the Holocene thermokarst lake formation and drainage into these ice-rich sediments left behind kilometer scale DTLBs. Subsequent generations of these form nested macro-environments for soil formation clearly visible in the satellite image and the LCC. Within these different generation of DTLBs, ice-wedge polygon formation is prominent and influencing soil formation at the meter scale.

The tundra total ecosystem C content is 28.6±2.9 kg C m\(^{-2}\) including the PC and the 0-100 cm SOC. The PC is 0.7±0.1 kg C m\(^{-2}\) and is a minor component in the total ecosystem C stock. Regarding the mean carbon for the three geomorphological units, the wetland classes in the DTLBs have the highest mean carbon and also the highest carbon content at landscape scale. The Holocene soils on the Yedoma remnants store intermediate amounts of carbon, but also cover a small area. The floodplain classes have the lowest carbon content and also cover little area (Figure 9a).
Figure 8: Land cover classifications for the study areas. a) Total extent of the Kytalyk study area. b) Detailed view of the Kytalyk study area showing a Yedoma plateau at the bottom left, a round thermokarst feature covered by wet tundra classes in the upper half and a floodplain area at the bottom right. c) Total extent of the Spasskaya Pad//Neleger study area with the northern sampling points near Neleger and the southern points near Spasskaya Pad. d) Detailed view of the Spasskaya Pad study area showing different types of forest and minor thermokarst features covered by grassland and wetland classes.
The taiga study area is viewed as two different geomorphological units (Figure 8c, d). The northern area, Neleger is underlain by ice-rich Yedoma deposits with large ice-wedges at depths of 2 m or more and prone to thermokarst processes. The southern area, Spasskaya Pad, is underlain by sandy substrates of a Pleistocene age terrace of the Lena river. In the LCC, the northern part is visible as large areas of thermokarst lakes and partly drained thermokarst lakes with their characteristic dominance of grassland and wetland classes in (semi)circular features, separated by larch forest. In the South these classes also occur, but are less common and more confined to gullies draining towards the Lena river valley in the West.

The taiga total ecosystem carbon content is 27.2 kg C m\(^{-2}\) including only the first meter of SOC and 41.6±6.2 kg C m\(^{-2}\) including also the second meter. Again, the phytomass has a small share of the total ecosystem carbon storage with a weighted landscape mean of 3.9 kg C m\(^{-2}\). Of the forest classes, the larch forest and the forested wetland class have the highest amount of carbon, while the birch forest, recently burned forest and pine forest contain less carbon. The highest amounts of carbon are in the wetland class, where peat formation is very common. At the landscape scale the larch forest is the most important carbon storage storing as much as 43% of the total carbon (Figure 9b).

For both study areas, the multivariate ordination diagrams show, that the defined land cover upscaling classes form distinct groups. This suggests that class properties are relatively homogeneous and that classes are clearly distinguishable along the ordination gradients. This is viewed as a positive validation of the applied thematic upscaling approach. The NMDS diagrams indicate, that the C allocation, mainly defined by the SOC, is promoted by two factors, the first factor is the occurrence of peat accumulating environments and the second is cryoturbation and burial of soil horizons. These two soil processes lead to similar high SOC values per pedon. In both environments the landscape scale geomorphological setting defines the SOC storages. In the tundra these are overprinted by meter scale variability caused by the occurrence of ice-wedge polygons and in the taiga by ecosystem dynamics following gradients in soil moisture and texture.
Figure 9 Detailed ecosystem C partitioning for Kytalyk and Spasskaya Pad/Neleger. The height of the bars represents the percentage of the total ecosystem C storage. The subdivision shows proportion of organic, cryoturbated and mineral soil, which is further distinct into active layer and permafrost. The crosses show the percentage of land cover of the respective class of the entire landscape. The amount of total ecosystem C for the individual classes is indicated below (grouped by most common land cover type).
6.1.2. Paper II


The Lena River Delta is the largest delta of a river discharging into the Arctic Ocean. In this study we present data from 50 soil pedons from a study area at the apex of the delta. Three major river terraces are commonly distinguished in the Lena Delta and are referred to as the third, second and first terrace. The third terrace represents Pleistocene remnants of Yedoma type deposits of a mostly eroded paleo-surface (Figure 10). The second terrace is build up of sandy deposits and formed at the transition to the Holocene. The first terrace formed during the Holocene. Further, a present day floodplain with weak soil development and unvegetated alluvial sediments with almost no soil development can be distinguished (Schwamborn et al., 2002; Bolshiyanov et al., 2015). The soil pedons sampled in this study cover all these major geomorphological units, except the second terrace. These represent together ~80% of the total delta area of around 32 000 km² (Morgenstern et al., 2008; Schwamborn et al., 2002).

In the last years, the knowledge on permafrost-affected soils has advanced significantly, but detailed data on SOC storage and other properties, such as nitrogen storage or water and ice content will be necessary to estimate future permafrost carbon storages and using modeling approaches (Ping et al., 2015).

In this study we present new soil and upscaling data for the Lena River Delta. We mapped a subregion of the Lena River Delta according to geomorphological units (Figure 11). For this we used a novel data-fusion approach, where we combined a high resolution multi-spectral satellite image with a digital elevation model (DEM). All 50 sampled soil pedons were classified according
to the U.S. Soil Taxonomy (Soil Survey Staff, 2014). We describe and discuss the most common soil types. High vertical resolution soil data derived from the collected soil pedons is averaged and plotted into typical soil profiles for each geomorphological unit. These are presented in Figure 12. The key properties, expected to be relevant for synthesis and modeling studies, include the SOC content (kg C m$^{-2}$), C%, dry bulk density (g cm$^{-3}$), visible ice % and water %. We also discuss soil development from the occurrence of different soil master horizons on each geomorphological unit. Detailed soil data is combined with the LCC to upscale SOC storage per geomorphological unit in the mapped subregion of the delta.

![Image of Figure 11: Land cover classification of the study area in the Lena Delta. Including all sampling points of the field work. a) shows the land cover classification result using only spectral bands. b) shows the classification result using spectral bands and elevation.](image)

The LCC for this study is derived using a data-fusion process by including an elevation data-layer. This is compared with a LCC that relies only on spectral bands. The data-fusion LCC method shows a clear improvement over the traditional classification approach. The individual terraces of the delta are better distinguished by including elevation information into the process. Classification errors still occur, for example there should be no occurrence of thermo-eroding 3rd terrace at distance from the main plateau located in the center left of the LCC (Figure 11).

For the 50 classified soil pedons, we identified ten different Soil Taxonomy great-groups. The most common classified great groups are Aquiturbels (n = 14), which usually form on the rims of ice-wedge polygons and Aquorthels (n = 13) as well as Historthels (n = 8), which usually form in polygon centers. These soils are common on the third terrace, first terrace and the floodplain. Less developed Psammoturbels are common on the slopes of the eroding third terrace and Haplorthels and Psammorthels are typical for the alluvial river sediments. The individual geomorphological
units show well developed soils for the third and first terrace and decreasing levels of development for the eroding third terrace, the floodplain and the alluvial sediments.

Figure 12: Overview of the soil properties per geomorphological unit. The depth indicated in cm. The representation interval is in cm. See the column heads for the respective variables and units. The last column shows the amount of samples that contributed at any single mm depth interval.

The SOC storage was calculated for each geomorphological unit and partitioned into the depth intervals 0-30 cm and 0-100 cm. The highest SOC content was estimated for the third terrace with 38.4±12 kg C m⁻² (±stdv) in the 0-100 cm top soil interval. This is followed by the first terrace where it was estimated to 25.4±8 kg C m⁻². The other geomorphological units have lower SOC contents with the thermo-eroding third terrace having a SOC content of 22.6±10.7 kg C m⁻², the floodplain 18.1±6 kg C m⁻² and the alluvial sediments 9.6±5.9 kg C m⁻². The LCC was used to upscale these mean SOC values. For the mapped subregion we calculate a mean SOC storage of 19.9±2.2 kg C m⁻². The 95% confidence interval is calculated as ±11% and the 99% confidence interval with as ±15%.

This study shows a remarkable diversity of classified soils for such a small area. There is no distinct association of the geomorphological units with specific soil great-groups, but there is a clear trend for the SOC storage of the geomorphological units. The third and oldest terrace with the most developed soils has the highest SOC content and the alluvial sediments that show little to no soil development show the lowest SOC content. Improvements in the LCC are a prerequisite for more detailed upscaling of soil properties.
7. Discussion

This thesis represents a contribution to further constrain estimates of SOC stocks in the circumpolar-permafrost region. SOC storage from a total of 107 new soil pedons has been presented for three study areas (Kytalyk: 24; Spasskaya Pad/Neleger: 33 and the Lena River Delta: 50). The latest circumpolar estimate of SOC by Hugelius et al. (2014) is based on 1778 pedons for the 0–1 m interval. Thus, the data from this research will increase the amount of soil pedons of the NCSCD by ~6%. However, the data presented here is, from a circumpolar perspective, spatially highly autocorrelated. The soil pedons are restricted to three study areas and located within clusters of only a few kilometers and with the most common distance between individual pedons of 100 m. At the same time, it is important to replicate soil pedons from different ecosystems and soil types. In both papers a high variability of the SOC storage within and between individual classes is described. Thus, local high resolution landscape estimates of SOC, as requested by McGuire et al. (2009) seem an appropriate approach and important contribution to international research efforts. Figure 13 shows circumpolar SOC stocks from the NCSCD distorted by the density of soil pedons in the database. The three described study areas are located in proximity of already available soil pedons. While the presented studies allow very detailed insights into local scale SOC dynamics, future research should focus on closing remaining regional gaps, particularly across Siberia. Improving the heterogeneity of this database is a motivating longterm goal to work on carbon storage in permafrost affected soils.

Very high-resolution remote sensing allowed generating very detailed estimates of SOC. In paper 1 high-resolution (2 × 2 m) satellite images are compared with reduced resolution inlets at 30 × 30 m pixel size. An initial attempt to quantitatively compare classifications at both resolutions was discarded. It was found that a class definition conflict emerged. This was particularly the case when ice-wedge polygons were involved. At very high resolution a different combination of classes makes sense than at lower resolution. Therefore, different classes should be defined at lower resolution. It also became apparent in paper 1, that traditional pixel-based approaches without specific pre- or post-processing yield noise prone results. In paper 1 this was solved by applying different filter techniques to the LCC product. This paper also solely relied on satellite imagery with a low-spectral resolution of four bands. Beyond this, there are other remote sensing products available, including satellite imagery with high spectral resolution, DEMs and radar remote sensing products, as well as derivatives of these. Soil moisture for example has shown to be a very important environmental variable for SOC storage in paper 1 and can be addressed using a DEM or radar remote sensing products. In paper 2 a DEM layer was added to the original 4 band satellite image. The documentation shows a marked improvement of the final classification using this approach. These combined datasets can then be analyzed with more sophisticated classification approaches using segmentation algorithms or object based methods. The combination or “fusion” of these different types of remote sensing products for image classification has made great progress in the recent years (Liao et al., 2015). In paper 2 the combined product was therefore segmented into homogeneous zones prior to the classification. However, the largest source of uncertainty for upscaling of SOC remains the comparatively low replication of soil pedons in these remote periglacial study areas.
This thesis investigates SOC allocation along different environmental gradients. Paper 1 shows that despite a very large environmental gradient between the two study areas, of which one is located in tundra terrain and one in the taiga forest, the SOC storage in the top 1m is fairly similar. However, the active layer in the taiga environment is significantly deeper, reaching below 1 m depth. Therefore, also the interval of 0–2 m was quantified in the taiga area. Significantly more SOC is stored in the active layer in the taiga as compared to the tundra, where almost half of the SOC in the top 1 m is locked in the permafrost, making more SOC available for microbial decomposition in the taiga. The Lena River Delta study area is also a tundra environment. The landscape mean SOC storage is lower than in Kytalyk. This reflects the deltaic environment where much of the landscape is dominated by a recent floodplain and sandy alluvial sediments. These have experienced short time periods of soil formation compared to the stable first and third delta terrace where SOC storage values are comparable to Kytalyk.

In all investigated periglacial landscapes, the distribution of SOC is strongly affected by landscape-scale geomorphological features (kilometer scale variability). These are the occurrence of Pleistocene ice-complex deposits, also called Yedoma, the occurrence of DTLBs, and alluvial or floodplain sediments. In the lowland tundra landscape (Kytalyk and Lena River Delta) this landscape-scale variability is overprinted at meter-scales by geomorphological features unique to permafrost environments, like ice-wedge polygons and non-sorted circles. This is well documented in the Lena Delta soil inventory with the occurrence of specific soil types within only a few meters. In the investigated taiga environment at Spasskaya Pad/Neleger, substantial meter-scale variability is caused by differences in environmental gradients like the catenary position, soil texture and forest successions, rather than small-scale periglacial landforms.

The background section of this thesis highlights the state factor of soil formation concept by Jenny (1941, 1980). While this concept is implicitly underling many methods and our general understanding of soils, it has not found its way into the papers presented here. Soil development in Spasskaya Pad can largely be described along environmental gradients. Soil properties shift from dry sandy soils on upper slopes towards organic rich moist sinks (Ohta et al., 1994). However, for the Yedoma affected area in Neleger, in Kytalyk and the Lena River Delta these assumptions are harder to acknowledge. I suggest that the underlaying ice content and rapid landscape development caused by thermokarst does not allow soil development in similar fashion along environmental gradients as in the investigated taiga site, where the landscape in general has more longterm stability. This has been implicitly stated in the articles, by addressing the role of Yedoma deposits and thermokarst dynamics for the distribution of soil types and SOC storage. The analysis of state factors of soil formation could be used in the future to improve the understanding and quantification of SOC storage in periglacial terrain and help to project future changes in the permafrost carbon pool caused by climate change. Periglacial landscapes are more affected by non-linear or non-gradual property changes than mid-latitude landscapes. These abrupt changes or mostly associated with the occurrence (or absence) of permafrost, the occurrence of massive or near-massive ice and the abundance of thermal isolating peat. The spatial distribution of different-ground ice types and the influence of permafrost degradation on landscape dynamics have recently been voted two out of
five top future research priorities within permafrost science by early career scientist (Fritz et al., 2015).

Figure 13 This cartogram shows the circumpolar SOC storage for the top meter gridded with a resolution of 1°, distorted by the amount of soil pedons in the database per 1°. Large regions in Siberia and Canada shrink together, indicating very low representation in the database. The two regions with the highest replication of soil pedons are Alaska in North America and the Usa River Basin and the West-Siberian Lowlands in Russia. These are followed by western Canada and the coast of the Laptev Sea in Russia. These areas appear large in the distorted overlay. The shrinkage of vast areas of the Arctic and Subarctic indicates, that they are not well represented with soil pedons in the database.
8. Conclusions

This Kappa and the papers 1 and 2 in the appendix present results and insights from high-resolution mapping of SOC and the documentation of soil properties in three study areas in Siberian periglacial terrain.

The two articles contribute to international efforts to quantify circumpolar SOC stocks. The data shows that there can be a great variability at local scale and that soil pedon data is still the limiting factor for our understanding of SOC stocks in Siberia. A particular value of this study is the high replication of all different landscape classes. Future research should focus on further decreasing regional gaps of soil pedon data.

The upscaling of SOC in this thesis is performed using high-resolution land cover maps. Paper 1 uses a comparatively traditional approach. Paper 2 builds on this experience by combining the satellite image with a DEM. It was then segmented into homogeneous areas and classified using a support-vector algorithm. This approach shows promising results.

It is argued that the concept of state factors of soil formation, as brought forward by Jenny (1941, 1980) could be a valuable framework to better understand present day SOC allocation in periglacial terrain and a good basis for future projections of the permafrost carbon pool.
9. Acknowledgements

I would like to particularly thank my supervisor Gustaf Hugelius for his support, his scientific input, the fruitful discussions, his patience and for being there whenever needed.

Furthermore, I would like to thank my co-supervisor Peter Kuhry for his assistance, feedback and support.

I would also like to thank all my co-authors for their contribution to this work. Without their man and woman power this research would not have been possible. Thanks to all my other colleagues and office mates. Thanks to Elin Högström for the great company in the project and the good collaboration. Thank you to my friends and family for their support and distraction.
A particular thank goes to the local partners and people maintaining the field stations that we visited throughout the different field seasons. Without their efforts this work would not be possible. The food in Spasskaya Pad will always have a place in my heart.

I would like to thank Birgit Heim and Frank Günther, AWI for their contribution of remote sensing data to paper II.

This research has been funded and supported by the EU FP7 PAGE21 project. The fieldwork was supported by the EU FP7 INTERACT Integrating Activity. Other financial support came from the Climate Research School (CRS) at the Bolin Centre, Mannerfelts fond and Ahlmanns fond.

I wish to thank Alev for being there for me.
10. References


