Abstract

High latitude terrestrial ecosystems are considered key components in the global carbon (C) cycle and hold large reservoirs of soil organic carbon (SOC). To a large degree, this SOC is stored in permafrost soils and peatlands and is vulnerable to remobilization under future global warming and permafrost thawing. Recent studies estimate that soils in permafrost regions store SOC equivalent to ~ 1.5 times the global atmospheric C pool. Ecosystems and soils interact with the atmospheric C pool: photosynthesis sequesters CO$_2$ into SOC whereas microbial decomposition releases C based trace gases (mainly CO$_2$ and CH$_4$). Because of the radiative greenhouse properties of these gases, soil processes also feedback on the global climate system. Recent studies report increases in permafrost temperatures and under future climate change scenarios permafrost environments stand to undergo further changes. As permafrost thaws and surface hydrology changes, there is concern that periglacial tundra and peatland ecosystems will switch from being sinks for atmospheric C into sources, creating a potential for positive feedbacks on global warming. The magnitude of change in C fluxes resulting from climate warming and permafrost thawing depends on the remobilization processes affecting SOC stores, the size of SOC stores that become available for remobilization and the lability of the SOM compounds in these stores. While the large size and potential vulnerability of arctic SOC reservoirs is recognized, detailed knowledge on the landscape partitioning and quality of this SOC is poor.

Paper I of this thesis assesses landscape allocation and environmental gradients in SOC storage in the Usa River Basin lowlands of northeastern European Russia. The Russian study area ranges from taiga region with isolated permafrost patches to tundra region with nearly continuous permafrost. Paper II of this thesis investigates total storage, landscape partitioning and quality of soil organic carbon (SOC) in the tundra and continuous permafrost terrain of the Tulemalu Lake area in the Central Canadian Arctic. Databases on soil properties, permafrost, vegetation and modeled climate are compiled and analyzed. Mean SOC storage in the two study regions is 38.3 kg C m$^{-2}$ for the Usa River Basin and 33.8 kg C m$^{-2}$ for Tulemalu Lake (for 1m depth in mineral soils and total depth of peat deposits). Both estimates are higher than previous estimates for the same study areas. Multivariate gradient analyses from the Usa Basin show that local vegetation and permafrost are strong predictors of soil chemical properties, overshadowing the effect of climate variables. The results highlight the importance of peatlands, particularly bogs, in bulk SOC storage in all types of permafrost terrain. In the Tulemalu Lake area significant amounts of SOC is stored in cryoturbated soil horizons with C/N ratios indicating a relatively low degree of decomposition. As this pool of cryoturbated SOC is mainly stored in the active layer, no dramatic increases in remobilization are expected following a deepening of the active layer. However, recent studies have demonstrated the importance of SOC storage in deep (>1m) cryoturbated horizons. Perennially frozen peat deposits in permafrost bogs constitute the main vulnerable SOC pool in the investigated regions. Remobilization of this frozen C can occur through gradual but widespread deepening of the active layer with subsequent talik formation, or through more rapid but localized thermokarst erosion.
This thesis consists of a summary and two papers. The papers are referred to by roman numerals.

**Paper I:**

**Paper II:**
Hugelius, G., Kuhry, P., Tarnocai C. and Virtanen T. Total storage and landscape distribution of soil organic carbon in the Central Canadian Arctic. Submitted to *Permafrost and Periglacial Processes*.

**Paper I** is a meta-analysis of data collected by many researchers during previous research projects. I compiled the data and did all statistical and geomatic analyses. I did most of the writing and constructed figures and tables. Peter Kuhry participated in interpretation of results and writing.

For **Paper II**, Peter Kuhry, Charles Tarnocai and Tarmo Virtanen did the field sampling and data collecting. I did most of the chemical analyses and all data processing, statistical analyses and geomatic analyses. I did most of the writing and constructed figures and tables. Peter Kuhry, Charles Tarnocai and Tarmo Virtanen participated in interpretation of results and writing.
SOIL ORGANIC CARBON IN PERMAFROST TERRAIN
Total storage, landscape distribution and environmental controls

A wider perspective on soil organic carbon

The origins of soil organic matter

Soil organic matter (SOM) is defined as the mixture of recognizable plant and animal detritus and material that has been altered so that it no longer contains its original structure (Oades 1989, in this thesis also including SOM in peat deposits and lake sediments). SOM is rich in carbon (C) and accumulates over time as organic detritus from biota is incorporated into mineral soils and peat deposits. The main source of organic detritus is from photosynthetic plants sequestering atmospheric carbon dioxide (CO$_2$). However, decomposition of organic material by soil microbes (soil respiration) returns C to the atmosphere, mainly as CO$_2$ or methane (CH$_4$). These dual fluxes of C maintain a turnover, or cycling, of soil organic carbon (SOC) pools.

The formation of SOM attracted the attention of 19th century naturalist Charles Darwin whose last work (Darwin 1881) described the role of earth worms in SOM formation. Meanwhile, contemporary Russian geographer Vasily Dokuchaev was developing the ideas that laid the foundations of modern soil science (Dokuchaev 1898, in Jenny 1980). During extensive travels throughout the Eurasian continent, Dokuchaev made observations on the linkages between biota, climate, topography and soil. Hans Jenny (1930, 1941) expanded on Dokuchaev’s work and did pioneering efforts in describing pedogenic processes and the formation of SOM along environmental gradients. He formulated semi-quantitative equations of soil forming processes and confirmed links between soil carbon inventories and pedogenic factors, i.e. parent material, climate, biota, topography, hydrology, human influence and time (Jenny 1980).

Soils in the global C cycle

Today, the integral role of soils in the global C cycle is well recognized (figure 1). The very first attempt at quantification of the global SOC pool was made by Waksman in 1938 (estimated 400 Pg global pool, Pg = g*10$^{15}$). Schlesinger (1977) made the first comprehensive quantification based on global ecosystem distributions, thereby producing a benchmark study. He presented separate estimates for a range of ecosystem types (1456 Pg total pool, 173 Pg in “Tundra and Alpine”, 137 Pg in global “Swamp and Marsh”) and established the importance of soils in the global C cycle. Post et al. (1982) made estimates based on world life zones, providing a global estimate (1395 Pg) and estimates for the different life zones (192 Pg in “Tundra”, 202 Pg in “Global Wetlands”). Bohn (1982) estimated global storage from the FAO Soil Map of the World to be 2200 Pg (with 400 Pg in peatlands). Most recent global estimates converge around 1500-1600 Pg for the top meter of global soils, with an additional 500-900 Pg of SOC stored in the second meter (Eswaran et al. 1993, Batjes 1996, Jobbagy and Jacksson 2000, Kirschbaum 2000, Amundson 2001).
Soil Organic Carbon in northern environments

Gorham’s (1991) review on northern peatlands highlighted the importance of northern peat deposits in C cycling and storage (an estimated 455 Pg in peatlands of boreal forests and tundra regions.). Based on the Northern Circumpolar Soil Carbon Database (NCSCD, Tarnocai et al. 2007), Tarnocai and Broll (2008) estimated the SOC storage in northern permafrost regions to be 496 Pg, of which 238 Pg is stored in peatlands (calculated to 1 m depth in mineral soils and to full depth in peat deposits). Schuur et al. (2008) included deeper mineral deposits (to 3 m depth) and estimated SOC storage in circum-arctic permafrost regions to be 1024 Pg, with peatlands contributing 277 Pg.

Results from these and other studies focusing on SOC storage in permafrost terrain (see also Zimov et al., 2006; Ping et al., 2008; Tarnocai et al., in press), suggest that frequently cited estimates of global SOC stores (Schlesinger 1977 and 1997, Post et al. 1982, Jobbagy and Jackson 2000) may underestimate storage in subarctic and arctic ecosystems by a factor 2 or more to 1 m depth and a factor ~3.5 to 3 m depth. The lower global estimates may be caused by an underestimation of storage in cryoturbated horizons of permafrost soils and peatlands (see e.g. Kuhry et al. 2002, Bockheim 2007, Tarnocai and Broll 2008, Ping et al. 2008, Papers I and II of this thesis). However, comparison between different studies is difficult as terminology and definitions differ, as do the definitions and sizes of the upscaling regions. The northern permafrost regions (18.7 * 10^6 km^2 of land outlined by Brown et al., 1997) used in the studies of Schuur et al. (2008) and Tarnocai and Broll (2008) include alpine and tundra ecosystems (~8.8 * 10^6 km^2 in global estimates), as well as regions of boreal forest in North America and Siberia (boreal forest cover ~12 * 10^6 km^2 in global estimates).

Northern soils in a changing environment

From the 19th century, following the end of the Little Ice Age in the Arctic, temperatures in arctic regions have increased significantly (Overpeck et al. 1997). Since the start of the industrial revolution the global average temperatures have risen by ~0,6°C (ACIA 2004). In the last few decades average temperature increases in the Arctic have been near twice as high as mean global increases (ACIA 2004). Under many future climate change scenarios, permafrost environments stand to undergo massive changes (Stendel and Christensen 2002). The IPCC predicts increases above global averages in arctic mean temperature and winter precipitation (Christensen et al. 2007), both key factors regulating permafrost distribution. Recent warming of permafrost has been reported (Lemke et al. 2007). In Alaska and Siberia, permafrost thaw is changing the size and distribution patterns of thermokarst lakes (Yoshikawa and Hinzman 2003, Smith et al. 2005).

Upland soils and peatlands in permafrost regions hold a large SOC pool. Northern peatlands have been expanding throughout the Holocene, sequestering C and acting as a sink for atmospheric C (Smith et al. 2004). However, as permafrost thaws and surface hydrology changes, there is concern that periglacial ecosystems will switch from being sinks for atmospheric C into sources, creating a potential for positive feedbacks on global warming (Oechel et al. 1993, Heikkinen et al. 2004). The surface hydrology of peatlands is a key factor regulating the exchange of C greenhouse gases,
as it affects soil respiration. Respiration by aerobic microbes in aerated soils and peat deposits primarily leads to \( \text{CO}_2 \) emissions, while \( \text{CH}_4 \) is the main by-product of anaerobic decay in waterlogged peat deposits or thermokarst lakes (Christensen et al. 2008). While most northern peatlands sequester \( \text{CO}_2 \), they are an important source of \( \text{CH}_4 \), contributing 3 to 5\% of global \( \text{CH}_4 \) emissions (Frolking et al. 2006). On a 100 year timeline, the greenhouse warming potential of \( \text{CH}_4 \) is 25 times that of \( \text{CO}_2 \) (Forster et al. 2007). As a consequence, on shorter timescales, a peatland can maintain net sequestration of \( \text{CO}_2 \)-C through photosynthesis (leading to sustained peat accumulation), while sustained \( \text{CH}_4 \) emissions (from anaerobic decay of SOM) lead to a positive net radiative forcing. However, because of the relatively short mean residence time (MRT) of \( \text{CH}_4 \) in the atmosphere, the long term effect over millennial timescales is a negative net radiative forcing (Frolking et al. 2006).

Gruber et al. (2004) identified permafrost soils and peatlands to be key C pools (together with oceans and forests), vulnerable to remobilization through permafrost thaw and changed surface hydrological conditions (figure 1).

![Figure 1](image_url)

Figure 1. Photograph on the left shows thermokarst developing in thawing palsa, Tavvavuoma, North-Western Sweden. Photograph on the right shows close-up of segregated ice inside the eroding palsa. Cryosuction has freeze-dried the fen peat surrounding the ice (pen added for scale).

An estimated half of the global SOC pool consists of refractory compounds. They account for a disproportionate amount of long-term terrestrial carbon storage due to their long MRT in soils (Amundson 2001). But general knowledge concerning the absolute and relative sizes of labile and recalcitrant SOC pools in the Arctic is poor. The intrinsic chemical lability of SOM compounds varies with botanical origin (Kuhry et al. 1996). Other environmental factors that affect the MRT of SOC include protection within soil aggregates or through electro-chemical bonds, drought, flooding and subzero temperatures (Davidson and Janssens 2006). While the latter is an obvious rationale for focusing on permafrost soils, the other factors are also susceptible to change if permafrost thaw alters the physical environment. A rapid response to environmental changes can be expected from labile SOC compounds, and improved knowledge of these SOC pools is crucial for predicting transient responses of high latitude soils in this century.

There are many potential feedback mechanisms on global warming that may affect C fluxes between high latitude soils and the atmosphere. The magnitude of change in C...
fluxes resulting from global warming and permafrost thawing depends on: (i) the nature, rate and extent of remobilization processes affecting SOC stores, (ii) the size of SOC stores that become available for remobilization and (iii) the lability of the SOM compounds in these stores. Improved process understanding is a research challenge that is currently being met by a diverse scientific community.

**Objective of PhD-project**

Although there is a scientific consensus that arctic and sub-arctic ecosystems harbour large reservoirs of SOC, detailed knowledge concerning the exact amounts, distribution and quality of SOC is lacking. The main objective of my PhD-studies is to: (1) assess the quantity, distribution and quality of SOC in permafrost terrain. Other objectives are to: (2) assess the quality and susceptibility to decay of SOM in permafrost and evaluate the possibility of using low-cost methods for this purpose (C/N ratios and peat colorimetry); (3) improve the understanding of environmental controls on SOC storage and quality through multivariate analyses; (4) further develop current geomatic methodology for soil sampling and upscaling results at local-regional scales; (5) a final goal of the PhD-project is to provide a synthesis comparing results from different types of permafrost terrain (from sporadic to continuous) in different climatic and geographical settings (continental to maritime, lowland to alpine).

The main study area is the Usa River Basin, North Eastern European Russia. A regional analysis of this area is presented in Paper I. In addition, detailed landscape level inventories of SOC were conducted in the Usa Basin and in more southerly taiga areas in 2007-2008. Results from these studies will form the basis for future work. Additional study areas are Lake Tulemalu in Central Canada (Paper II), Tavvavuoma in northern Sweden (fieldwork 2007-2009) and Zackenberg in North Eastern Greenland (fieldwork 2009). Figure 2 shows the location of all study areas on a circum-arctic map.

![Circum-arctic map](https://via.placeholder.com/150)

**Figure 2.** Circum-arctic map showing the locations of present and future study areas.
Upscaling methodology and statistical analyses

Global studies of SOC storage

Attempts to estimate global SOC stores through the link to vegetation have typically used an approach where the arithmetic mean of SOC storage from a number of sites within a biome or life zone are multiplied by the respective region’s areal coverage. Most global estimates of SOC suffer from a poor sample representation in large and remote high-latitude areas. The combined "Tundra and Alpine Ecosystems of the World" (~ 8.8 * 10^6 km^2) are represented by 21, 48 and 51 sites in the studies by Schlesinger (1977), Post et al. (1982) and Jobbagy and Jackson (2000), respectively.

The main challenges to overcome are availability of reliable global SOC data and finding a reliable upscaling proxy with global coverage. The choice of upscaling proxies is essentially limited to satellite land cover classifications (LCC:s) or soil maps. A difficulty with global LCC:s is development of a classification system that works across the diverse regions of the Earth. Maintaining thematic accuracy and translating different thematic classes across regions is a challenge, but there are promising products and initiatives that could be useful in SOC upscaling (GLC 2000 and 2002, NASA 2007). There are quite extensive global soil databases available for use in upscaling, ordered according to international standardized soil classification schemes (FAO 1995, Batjes 2002). However, they suffer some drawbacks that may limit their usability for more detailed studies of SOC storage. Many pedons lack values for soil bulk density and C % content, variables that are needed to calculate SOC storage.

Local and regional SOC studies in the Arctic

Local or regional scale studies of SOC storage in remote arctic areas have typically used an upscaling approach similar to global studies, but with greater spatial and thematic resolution (e.g. Michaelson et al. 1996, Tarnocai and Lacelle 1996, Kuhry et al. 2002, Mazhitova et al. 2003). Estimates of total storage in the investigated landscape are based on an upscaling methodology where an empirical connection between nominal vegetation or soil classes and SOC storage is established through in situ sampling of soils. Areal coverage is subsequently obtained through a satellite LCC or regional soil map. The estimated mean SOC storage in each land cover or soil class is multiplied by the areal coverage of that class.

As this upscaling method is based on arithmetic means of sites the standard error of the mean (SE= StD/√n), is a logical statistical measure of accuracy. The best way to directly affect SE is to increase site density (number of sites per upscaling unit) of the estimate. But to get an accurate result, the site selection must provide a correct representation of the landscape that is being upscaled. A narrow site selection (e.g. insufficient representation of deep peatlands or cryoturbated soils) may not fully represent the variety present in the landscape. This leads to a low StD in the upscaling dataset, causing an illusion of upscaling accuracy as the SE remains low.

There are a number of inherent assumptions that you accept when you upscale by multiplying the mean SOC storage of a class with spatial coverage. You assume that the selected upscaling classes (land cover or soil classes) accurately depict the diverse
natural environment of the landscape you are describing and that all upscaling classes are separate statistical populations that can be accurately described through empirical studies. Any gradients or ecotones within the upscaling classes are ignored (or more accurately they are described by a large SE). There are some ways to approach the fulfillment of above mentioned criteria by simple statistical tests. The data within each class should be (log)normally distributed and unimodal. Furthermore, data from all upscaling classes can be compared in student t-test to see whether they do form separate populations.

One of the challenges with estimating arctic soil C pools is the construction of a sampling program that correctly describes the environment. The arctic landscape displays variation on many different spatial scales, and different methods for calculating landscape C pools demand varying approaches to sampling. In field studies we have used either a transect based sampling method, or a weighted stratified random sampling approach. The transect approach involves a subjective selection of ‘representative’ transect locations following field reconnaissance. Once transects are established, soil samples are collected equidistantly without further subjective bias. This sampling scheme combines selective representation of what is considered representative in the landscape with a measure of randomization introduced by small-scale vegetation and micro-topography patterns. In stratified random sampling program, the study area is subdivided a priori, based on a preliminary LCC, and a weighted number of sampling sites are randomly distributed within each class. The weighting of sites is based on the expected variability in SOC storage within the class (data from previous studies). While the latter is a statistically more sound approach (e.g. Simbahan and Dobermann 2006), it is labour intensive and consumes more field time (mainly because of longer distances between sites).

**Multivariate statistical analyses**

Multivariate gradient analysis techniques, such as Principal Component Analysis (PCA), allow integrated analysis of multiple variables on different scales of measurement (Jongman et al. 1995, Kent 2006). In Papers I and II, we use PCA to investigate connections between site specific soil properties and a range of environmental variables (vegetation, climate and permafrost). In Paper I, constrained gradient analyses (Redundancy Analysis, RDA) is combined with Monte Carlo permutations to model connections between soil properties, permafrost, vegetation and climate.

PCA is an unconstrained ordination technique commonly used for reducing dimensionality and extracting patterns from multivariate datasets with linear responses to gradients of change. PCA calculates theoretical variables (termed Principal Components, PCs) that minimize the residual sums of squares between all observations in a multidimensional matrix and the PC axes. All PCs are orthogonal in multidimensional space (i.e. completely uncorrelated), maximizing the amount of information that is retained in each PC.

In earth-science and ecology there are several direct gradient analysis methods in use, these are generally ordination based techniques that are expanded to include the influence of external independent variables, or environmental gradients (Wagner 2004, Kent 2006). RDA is an extension of PCA where the information contained in an explanatory dataset of environmental variables is used to constrain the response
variable dataset. For each site, it only extracts the information in the soil response variables that can be explained through variations in the environmental variables. In RDA the ordination axes are derived from PCA and the technique assumes a linear response model (as opposed to a Gaussian response model used in Canonical Correspondence Analysis). The intended use of RDA analysis is to relate the abundance of a set of species (dependent variables, Dataset 1) to data describing a suite of environmental variables for the sampling sites (independent variables, Dataset 2).

In an extension of RDA, Monte Carlo permutations are used to evaluate the null hypothesis that soil response variables are unaffected by environmental variables (Ter Braak and Smilauer 2002). In what is called a “Forward Selection of variables”, the environmental variable with the highest explanatory power is tested first (and included if the p-value is accepted) after which the explanatory power of the remaining variables are recalculated, factoring in the variance already accounted for by the included variable. The process is used to avoid over-fitting the RDA model with redundant environmental variables.

A spatial matrix based on geographical locations of sampling sites can be used to partial out spatial autocorrelation and ecoclimatic location from the dataset, allowing more direct analyses of the impact of other environmental variables (implemented in Paper I). A matrix is constructed by adding all terms for a cubic trend surface regression (Borcard et al. 1992). To avoid over-fitting of the model, stepwise Forward Selection of variables is used to identify the variables with highest explanatory power. Multivariate ordination techniques, coupled with Monte Carlo permutations and co-variable matrixes have proved to be good tools for investigating complex relationships between soil properties and the environment. Future work will include modeling of spatial structures and autocorrelation in SOM distribution through variance partitioning (Peres-Neto et al. 2006) and semivariogram modeling (Wagner 2003, Wagner and Fortin 2005).
Summary of the papers

Paper I


In this study we describe the landscape distribution, quantity and quality of SOM (including SOC storage in upland soils, lake sediments and peat deposits) across the lowland taiga-tundra continuum of the Usa River Basin, northeastern European Russia (93 500 km², figure 3). The study area ranges from taiga with isolated patches of permafrost in the South, through the taiga-tundra transition zone with discontinuous permafrost to tundra and continuous permafrost in the North.

Figure 3. The large map shows main vegetation patterns and boundaries of the regions defined for upscaling: 1. taiga region 2. (forest)-tundra region, and 3. mountain region. No vegetation data is shown for the mountain region. The inset map shows the location of the Usa River Basin and the Pechora and Ob rivers (west and east of the basin, respectively). Sites used for ordination and upscaling analyses are shown (an additional 23 taiga sites and 87 (forest)-tundra sites are lacking exact coordinates and are not displayed). Projection UTM 40 N (WGS 84).

We compile and analyse databases describing soil chemical and physical properties, permafrost conditions and vegetation for 325 separate sites across the taiga-tundra continuum. Previous estimates of landscape SOC storage in the Usa Basin (see Kuhry et al. 2002) are revised and updated with new calculations and addition of new sites. We describe the partitioning of SOC in 24 different vegetation types, also including estimates of SOC storage in permafrost soils (above and below the active layer boundary). A subset of the database is analyzed in multivariate gradient analyses to determine how an array of environmental variables are interconnected and linked to site specific SOM quantity and quality. Constrained gradient analyses with Monte
Carlo permutations are used to model connections between SOM, permafrost, vegetation and climate patterns.

Mean SOC storage in taiga and (forest)-tundra regions are estimated at 37.3 and 38.7 kg C m$^{-2}$, respectively. Peatlands account for 72\% of SOC storage with only 30\% of the surface area (figure 4). Permafrost within the upper meter (signifying Cryosols or cryic Histosols) is found in 13\% of investigated sites. These permafrost soils store 42\% of the total SOC pool, of which nearly three quarters is perennially frozen below the active layer. Peatlands hold 95\% of all SOC in permafrost terrain and 98\% of all perennially frozen SOC, mainly in bog peatlands of the (forest)-tundra region. Multivariate gradient analyses further emphasize the role of bog peatlands in SOC storage. SOM stored in permafrost has higher C/N ratios than unfrozen material, indicating that this material is more labile and susceptible to decay if thawed.

![Figure 4](image_url)

Figure 4. Graph shows the estimated percentage of total land cover and total soil C storage (bars) for different land cover types in the taiga and (forest)-tundra regions. The bars are subdivided to show storage in non permafrost soils as well as storage above and below active layers in permafrost soils. Some of the land cover types used for upscaling have been amalgamated into groups.

Gradient analyses of climatic patterns show that at this regional scale, site permafrost is equally affected by temperature and precipitation variables. Site vegetation and permafrost are strong predictors of soil chemical properties, also when regional ecoclimatic patterns are accounted for (through introduction of a spatial co-variable matrix). While site permafrost loses its predictive power when the vegetation co-variable is used, vegetation remains a strong predictor despite introduction of co-variables and explains a significant part of the variance in soil properties. Local vegetation and permafrost conditions overshadow the effect of climate variables on soil properties. Introducing co-variables to mask out the local conditions shows that a
The combination of mean annual air temperature and annual precipitation is a strong predictor of site specific soil properties.

The results from this study highlight the importance of permafrost bogs as stores of large amounts of labile C. It is important that the representation of these SOC hotspots in global C estimates and models is as accurate as possible. Permafrost bogs are common throughout the sub-arctic and arctic, often found in areas no longer climatically optimal for permafrost formation (Christensen et al. 2004). Permafrost thaw resulting in remobilization of this frozen SOC pool may occur through deepening of the active layer or through thermokarst formation. Active layer deepening is a gradual process with large areal extent that may eventually lead to talik formation (a layer or body of perennially unfrozen ground occurring in permafrost terrain). Thermokarst formation is more localized but may occur rapidly, generally leading to altered surface hydrological conditions. While there is evidence for the active occurrence of both active layer deepening and thermokarst (Lemke et al. 2007), the relative and total magnitude of changes in C fluxes resulting from these processes remain uncertain.

**Paper II**

Hugelius, G., Kuhry, P., Tarnocai C. and Virtanen T. Total storage and landscape distribution of soil organic carbon in the Central Canadian Arctic. Submitted to *Permafrost and Periglacial Processes*.

A substantial part of high latitude stores of SOC are found in the Canadian Arctic. Tarnocai and Lacelle (1996) concluded that peatlands and permafrost soils contained the largest total SOC masses in Canada, respectively storing 106 Pg and 103 Pg SOC. Tarnocai (2006) subsequently updated the C storage estimate for Canadian peatlands (1.1 million km$^2$) to 147 Pg SOC and predicts that 60 % of Canada’s peatlands are expected to be severely or extremely severely affected by projected climate change. Permafrost temperatures in Canada have been rising since the mid-1990s (Brown et al. 2000, Smith et al. 2003, Smith et al. 2005).

Only generalized soil C inventories are available for large parts of the Canadian Arctic.

In this study we assess the total storage and spatial distribution of soil C in continuous permafrost terrain of Central Canada. The study area is located on the shore of Tulemalu Lake (62° 55´ N, 99° 10´ W, figure 5) in the Low Arctic zone, 100 km north of the treeline. Mean annual temperatures in the area are between - 9.4 to -14.3 °C and total annual precipitation is < 300 mm. The region is located in the Continuous Permafrost Zone, with low to medium ice content. Deglaciation of the Laurentide ice occurred between 9000-8000 cal yrs BP.
The landscape allocation of soil C is assessed using a transect-based soil sampling program in a 21 km² study area. We compare upscaling using transect vegetation inventories to full landscape upscaling using land cover data derived from Landsat 7 ETM+ satellite imagery. We analyse the partitioning of soil C in surface organic deposits and peat deposits, deeper cryoturbated organic pockets and the mineral subsoil, also separating active layer from permafrost storage. The quality of soil organic compounds is assessed using C/N weight ratios. Basal peat and cryoturbated pockets of organic matter have been AMS ¹⁴C dated to describe the Holocene landscape development of the study area.

Mean SOC storage in the study area for 0-100 cm depth is estimated to be 33.8 kg C m⁻², which is much higher than previous estimates for this part of the Central Canadian Arctic (14-24 kg C m⁻²). The oldest basal and fossil wood dates indicate that peat deposits started to accumulate around ~6000 cal yrs BP, in a time when spruce was present in the study area. Bog peatlands hold 39 % of the total SOC pool, 58 % of organic deposits and 59 % of the perennially frozen SOC (figure 6). Fen peatlands cover larger areas than bogs, but store relatively little SOC (17 % of total). There are large differences in SOC storage between different upland tundra classes, following a landscape moisture gradient.

Radiocarbon dating of cryoturbated soil horizons shows that cryoturbation processes have been occurring in the study area since the Middle Holocene (~6500 cal yrs BP).
Cryosols developed on till parent material store significant amounts of SOC in buried cryoturbated soil horizons, contributing to 17% of the total storage for the 0-100 cm depth interval (mostly in the active layer). Using default values from the literature to include deeper (1–3 m) cryoturbated deposits and 30 cm of mineral subsoil underlying peat deposits significantly increases the mean landscape storage to 52.9 kg C m\(^{-2}\). Analyses of C/N ratios show that the organic matter in cryoturbated pockets is less decomposed than the organic matter in the surrounding mineral materials.
Summary of conclusions

Mean SOC storage in the two study regions is 38.3 kg C m\(^{-2}\) for the Usa River Basin and 33.8 kg C m\(^{-2}\) for Lake Tulemalu. Both estimates are higher than previous estimates for the same study areas. The results highlight the importance of peatlands, particularly bogs, in bulk SOC storage in all types of permafrost terrain. Peatlands hold 72% of SOC in the Usa Basin and 56% of SOC in the Tulemalu Lake study area. In all, 42% of SOC in the Usa Basin is stored in permafrost soils, and 30% of all SOC is perennially frozen below the active layer. In the continuous permafrost terrain of Lake Tulemalu all SOC is stored in permafrost soils, but the amount of perennially frozen SOC is 35%, similar to the Usa Basin. In the (forest)-tundra region of the Usa Basin there is a high prevalence of very deep frozen peat deposits and 98% of the perennially frozen SOC is stored in bog peatlands. Peat deposits at Lake Tulemalu are generally younger and shallower, leading to lower storage of SOC in perennially frozen peat.

Cryoturbation is an important process for burial of C rich soil horizons in continuous permafrost terrain in Canada (representing 17% of total SOC storage, mainly in the active layer), but seems of little importance in the Usa Basin lowlands. As a consequence upland tundra soils in Lake Tulemalu have higher mean SOC storage.

Multivariate gradient analyses show that local vegetation and permafrost are strong predictors of soil chemical properties, overshadowing the effect of climate variables. In the Usa Basin SOM stored in permafrost has higher C/N ratios than unfrozen material. Cryoturbated organic soil pockets in Lake Tulemalu have higher C/N ratios than the surrounding mineral horizons.

Permafrost bogs constitute the main vulnerable SOC pool in the investigated regions. Permafrost bogs are common throughout sub-arctic and arctic regions and it is important to have an accurate representation of these SOC hotspots for global estimates of C cycling. Remobilization of this frozen C can occur through gradual but widespread deepening of the active layer with subsequent talik formation, or through more rapid but localized thermokarst erosion. In the Lake Tulemalu area significant amounts of SOC is also stored in cryoturbated soil horizons with C/N ratios indicating a relatively low degree of decomposition. As this pool of cryoturbated SOC is mainly stored in the active layer, we would not expect dramatic increases in remobilization following a deepening of the active layer. However, recent studies have demonstrated the importance of SOC storage in deep (>1m) cryoturbated, mostly perennally frozen, horizons.
Ongoing work and future plans

The taiga-tundra continuum in northeastern European Russia

The study area of the CARBO-North research program (www.carbonorth.net) ranges from typical (permafrost free) boreal taiga near Syktyvkar in the south to continuous permafrost terrain in the north (figure 7). During two extended summer field campaigns in 2007 and 2008 I have carried out soil sampling programs in all designated study areas.

Figure 7. Overview of the CARBO-North study areas (1–4) in North-Eastern European Russia. 1. The Seida intensive study area. 2. The Rogovaya river (three study areas in transect across Forest-Tundra transition). 3. The Khosedayu study area. 4. The taiga study areas, Laly and Sludka. (source: www.carbonorth.net).

Within the Usa River Basin we have five study areas. In the Seida intensive study area we have sampled soils in an extensive program combining a transect approach to a weighted stratified random sampling scheme. Along the Rogovaya River, three separate study sites form a transect across the wide forest-tundra transition. The Khosedayu study area, furthest to the west, is in a different geological setting from the other areas. The results of the soil sampling programs and chemical analyses will be upscaled using high resolution satellite LCC.s provided within the CARBO-North project by colleagues from the University of Helsinki, Finland. The upscaling results will be integrated with results from phytomass inventories (from University of Helsinki) to increase understanding of C storage and cycling in the region.

A detailed inventory of thermokarst lakes in peat plateaus in Seida and at the Rogovaya River was carried out (figure 8a). The results give information on lake morphology and processes behind thermokarst formation. Radiocarbon dating of selected soil and peat horizons and stratigraphic analyses helps in recreating the Holocene development of the study area. From the Seida intensive study area representative samples from all different vegetation types have been selected for more detailed analyses. In cooperation with colleagues from the Department of Geology and Geochemistry (Stockholm University) we have extracted the humic and fulvic
acid components from freeze-dried SOM. These extracts are analyzed for dissolved organic C content, elemental and stable isotope content for C, N and hydrogen (H). Using photo-spectrometry, absorption in different wavelengths is measured (400, 465, 600 and 665 nm). These combined analyses of humic and fulvic extracts will give us in depth information on the lability of SOM compounds stored in different landscape settings (Ikeya and Watanabe 2003). This will be combined with the landscape estimates of SOC storage and partitioning to provide an overall view of potential for SOC remobilization in the area.

We have also collected soil samples from boreal taiga catchments (figure 8b). The taiga study areas are located far south of the southern permafrost border, and are included as areas for comparison (analogue to future warming in current forest-tundra). The results from the taiga SOC inventories will be upscaled to full areal coverage and integrated with phytomass inventories performed by scientists from University of Helsinki, Finland.

In two taiga peatlands we have done transect based inventories of peat depth and basal peat ages (determined using $^{14}$C dating) to recreate late Holocene and current rates of paludification.

**Subarctic alpine tundra, Taavavuoma, NW Sweden**

Fieldwork in Tavvavuoma has been carried out at four occasions, two autumn trips and two winter trips. A third and final autumn trip is planned for September, 2009. In Tavvavuoma we have a wide research focus, encompassing SOC storage and partitioning, soil mapping, permafrost mapping and vegetation mapping. Several soil pits have been sampled and described following FAO terminology (1998, figure 9a). Nine complete thermokarst lake sediment cores have been collected during winter sampling. With the help of Russian scientists from Fundamentproject, Moscow, we have drilled deep boreholes for permafrost monitoring in two palsa complexes at different altitudes (to 10 and 6 m depth at elevations of 450 and 750 m.a.s.l., figure 9b). We are exploring the possibilities of doing permafrost mapping in the area by measuring the basal temperature of snow during late winter (King 1983, Heginbottom 2002). We are planning to conduct vegetation mapping at several spatial scales to
describe the effects of upscaling proxy resolution and accuracy (vegetation data from Landsat 7 ETM+, IKONOS and digital aerial imagery from Lantmäteriet).

Figure 9. Photograph to the left (a) shows a soil pit excavated through sorted circle in alpine tundra of the Tsåktso plateau, Tavvavuoma. Gradual movement of rocks through freeze-thaw cycles sorts rocks (accumulation of stones in the left part of the pit). Photograph to the right (b) shows the high elevation palsa mire where one of the deep permafrost boreholes has been drilled.

**High Arctic tundra in alpine terrain, Zackenberg, NE Greenland**

Zackenberg Research Station (74°28’ N, 20°34’ W) is located in continuous permafrost terrain on north-eastern Greenland. The research station is located at the bottom of a glacial valley in an alpine setting.

A ten day field campaign is planned to the Zackenberg research station in August, 2009. The goal is to carry out a distributed sampling program that can subsequently be upscaled using available proxy data from the Zackenberg station (maps of vegetation, soil and geomorphology). We will determine total storage and landscape distribution of SOC. Detailed geochemical analyses and ^14^C dating will provide information on the quality and age of stored SOM.
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