Estimated stocks of circumpolar permafrost carbon with quantified uncertainty ranges and identified data gaps

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Abstract

Soils and other unconsolidated deposits in the northern circumpolar permafrost region store large amounts of soil organic carbon (SOC). This SOC is potentially vulnerable to remobilization following soil warming and permafrost thaw, but SOC stock estimates were poorly constrained and quantitative error estimates were lacking. This study presents revised estimates of permafrost SOC stocks, including quantitative uncertainty estimates, in the 0 to 3 m depth range in soils as well as for sediments deeper than 3 m in deltaic deposits of major rivers and in the Yedoma region of Siberia and Alaska. Revised estimates are based on significantly larger databases compared to previous studies. Despite this there is evidence of significant remaining regional data gaps. Estimates remain particularly poorly constrained for soils in the High Arctic region and physiographic regions with thin sedimentary overburden (mountains, highlands and plateaus) as well as for deposits below 3 m depth in deltas and the Yedoma region. While some components of the revised SOC stocks are similar in magnitude to those previously reported for this region, there are substantial differences in other components, including the fraction of perennially frozen SOC. Upscaled based on regional soil maps, estimated permafrost region SOC stocks are 217±12 and 472±27 Pg for the 0 to 0.3 m and 0 to 1 m soil depths, respectively (±95% confidence intervals). Storage of SOC in 0 to 3 m of soils is estimated to 1034±150 Pg. Of this, 34±16 Pg C is stored in poorly developed soils of the High Arctic. Based on generalised calculations, storage of SOC below 3 m of surface soils in deltaic alluvium of major Arctic rivers is estimated to 91±52 Pg. In the Yedoma region, estimated SOC stocks below 3 m depth are 181±54 Pg, of which 74±20 Pg is stored in intact Yedoma (late Pleistocene ice- and organic-rich silty sediments) with the remainder in refrozen thermokarst deposits. Total estimated SOC storage for the permafrost region is ~1300 Pg with an uncertainty range of ~1100 to 1500 Pg. Of this, ~500 Pg is in non-permafrost soils, seasonally thawed in the active layer or in deeper taliks, while ~800 Pg is perennially frozen. This represents a substantial ~300 Pg lowering of the estimated perennially frozen SOC stock compared to previous estimates.

1 Introduction

As permafrost warming and thaw occurs, large pools of soil organic carbon (SOC) that were previously protected by sub-zero temperatures may become available for mineralization, leading to increased greenhouse gas fluxes to the atmosphere (Schuur et al., 2008). Incorporating permafrost related soil processes into Earth System Models (ESMs) has demonstrated that permafrost C and associated climate feedbacks have been underestimated in previous modelling studies and that high-latitude soil processes may further accelerate global warming (Koven et al., 2011; Schaefer et al., 2011; Burke et al., 2012; Schneider von Deimling et al., 2012).

At high latitudes, low soil temperatures and poor soil drainage have reduced decomposition rates of soil organic matter (SOM) (Davidson and Janssens, 2006). Over millennial timescales, processes such as cryoturbation, accumulation of peat and repeated deposition and stabilization of organic-rich material (alluvium, proluvium, colluvium or wind-blown deposits) have led to accumulation of permafrost SOC in mineral soils, peat deposits (organic soils), silty late-Pleistocene syngenetic organic- and ice-rich deposits (Yedoma), deltaic deposits and other unconsolidated Quaternary deposits (e.g. Ping et al., 1998; Tarnocai and Stolbovoy, 2006; Schirrmeister et al., 2011a; 2011b; Ping et al., 2011; Strauss et al., 2012). Using the Northern Circumpolar Soil Carbon Database (NCSCD), a digital soil map database linked to extensive field-based SOC storage data, Tarnocai et al. (2009) estimated the 0 to 0.3 m and 0 to 1 m SOC stocks in the northern circumpolar permafrost region to be 191 Pg and 496 Pg, respectively. Based on limited field data, but in recognition of the key pedogenic processes that transport C to depth in permafrost soils, Tarnocai et al. (2009) provided a first-order SOC mass estimate for 0 to 3 m soil depth of 1024 Pg. This 0 to 3 m estimate was based on 46 pedons in Canada and was not included into the spatially distributed NCSCD. Hugelius et al. (2013a) recently compiled an updated pedon data set for soils in the northern circumpolar permafrost region extending down to 2 m and 3 m depths (n=524 and 356, respectively), which were incorporated into an updated NCSCDv2 and is now available to improve characterization of the 1 to 3 m SOC stocks.

A first-order estimate of SOC stocks in Yedoma terrain of 450 Pg (Zimov et al., 2006) was calculated from a small-scale map of Yedoma extent (Romanovskii, 1993), using generalised data of Yedoma deposit thickness, massive ice content, organic C% and bulk density. This estimate was recalculated to 407 Pg to avoid double counting of SOC stocks in the top 3 m of deposits when included into a summative circumpolar estimate of Tarnocai et al (2009). Schirrmeister et al. (2011a) suggested that Yedoma SOC stocks may be 25% to 50% lower than previously reported because of overestimated mean bulk density value in Yedoma deposits. Using newly compiled data on deposit thickness, spatial extent of thermokarst, bulk density, segregated ice content and massive wedge-ice content, Strauss et al. (2013) provide an updated estimate of 211 Pg SOC (with an uncertainty range from 58 to 371 Pg) stored in permafrost sediments of the Yedoma region (including intact Yedoma and refrozen thermokarst sediment with Holocene cover deposits of Siberia and Alaska, not including active layer, thawed sediments underlying lakes and rivers or areas covered by deltaic or fluvial sediments).

Based on field data from the Mackenzie River Delta, Tarnocai et al. (2009) estimated SOC storage in the deltaic deposits of seven selected Arctic river deltas to be 241 Pg. Since this first-order estimate demonstrated the potential importance of deltaic permafrost deposits, new knowledge has become available regarding deeper SOC stores in Arctic Deltas. Field-studies from the Alaskan Beaufort Sea coast (Ping et al., 2011) and the Siberian Lena River Delta (Schirrmeister et al., 2011b; Zubrzycki et al., 2013) provide new information on SOC stocks in near-surface deltaic deposits. There is also additional information regarding the spatial extent and depth of deltaic deposits (Walker, 1998; Aylsworth et al., 2000; Smith et al., 2005; Johnston and Brown, 1965; Taylor et al., 1996; Schwamborn et al., 2002).

Tarnocai et al. (2009) provided a total estimate of circumpolar SOC storage in soils (0 to 3 m depth), Yedoma and deltaic deposits of 1672 Pg, of which 1466 Pg is stored in permafrost terrain. This is about twice as much C as what is currently stored in the atmosphere (Houghton, 2007). While it is recognised that this pool of SOC stored in permafrost regions is large and potentially vulnerable to remobilization following permafrost thaw, estimates are poorly constrained and quantitative error estimates are lacking (Mishra et al., 2013). Tarnocai et al. (2009) assigned qualitative levels of confidence for different components of the permafrost region SOC stock estimate. In recognition of the limited field observations on which estimates are based, estimates for SOC stocks stored in deep soil (1 to 3 m), Yedoma and deltaic deposits were assigned the lowest degree of confidence.

The aim of this paper is to update and synthesise the current state of knowledge on permafrost SOC stocks. We revise estimates of the permafrost SOC stocks for the 0 to 3 m depth range in soils as well as for deeper sediments in deltaic and Yedoma region deposits. Compared to previous studies (Tarnocai et al., 2009; Zimov et al., 2006), the number of individual field sites or pedons available for calculations has increased by a factor of 11 for 1 to 2 m soils, a factor of 8 for 2 to 3 m soils and deltaic alluvium and a factor of 5 for Yedoma region deposits. The first ever spatially distributed, quantified estimates for the 0 to 3 m depth range in soils are upscaled based on regional soil maps in the NCSCDv2. Estimates of 0 to 3 m SOC stock are calculated by separating physiographic regions of thick and thin sedimentary overburden, corresponding to lowland and highland areas, respectively (Heginbottom et al., 1993; Brown et al., 2002). In recognition of limited soil development in some high latitude regions (Horwath Burnham and Sletten, 2010), SOC stocks in thin soils of the High Arctic bioclimatic zone are upscaled separately. A revised estimate of SOC stocks in deltaic deposits is based on new field data and updated information to calculate the spatial extent and depth of deltaic alluvium. For the Yedoma region, the estimate of Strauss et al. (2013) is recalculated by implementing an updated methodology for estimating uncertainty ranges and removing spatial overlap with SOC stored in surface soils. The different components of the permafrost region SOC stocks are summarised and presented together with quantitative uncertainty estimates. A primary goal of this study is to quantify uncertainties associated with permafrost SOC stocks estimates, and to improve understanding of the permafrost SOC pool size and distribution for model simulations of the permafrost-carbon feedback on the climate system.

2 Methods

Below we present a summary of methods used to obtain our estimates. More detailed descriptions of methods, including the datasets used for different calculations, are available in the online supplemental material.

2.1 Calculating 0 to 3 m SOC stocks

Calculation of SOC stocks (absolute amount of SOC reported as either kg or Pg SOC) based on thematic soil maps is done in three steps (Hugelius, 2012). First, the SOC storage (SOC amount per area unit, given in kg C m^{-2}) for individual pedons (a pedon is a three-dimensional body of soil as sampled, described and classified in soil studies) is calculated to the selected reference depths. Second, the pedon data are grouped into suitable thematic upscaling classes, and mean SOC storage (with confidence intervals) for each class and reference depth is calculated. Finally, the mean SOC storage of each class is multiplied with estimates of the areal coverage of thematic upscaling classes to calculate total SOC stocks (including uncertainty ranges) for different classes and reference depths.

For this study, SOC stocks were estimated separately for the 0 to 0.3 m, 0 to 1 m, 1 to 2 m and 2 to 3 m depth ranges using the NCSCDv2. The NCSCDv2 is a polygon-based digital database adapted for use in Geographic Information Systems (GIS), which has been compiled from harmonised national or regional soil classification maps. Map data on soil coverage have been linked to pedon data with SOC storage from the northern permafrost regions to estimate geographically upscaled total SOC stocks (Hugelius et al., 2013b).

The SOC stocks estimates for the 0 to 0.3 m and 0 to 1 m depth ranges were calculated separately in each NCSCDv2-region (i.e., Alaska, Canada, Contiguous USA, Europe, Greenland, Iceland, Kazakhstan, Mongolia, Russia and Svalbard) following the methodology of Tarnocai et al. (2009) but using the revised and gap-filled datasets described by Hugelius et al. (2013a; 2013b). Separate SOC stock estimates were calculated for the High Arctic region. Outside the High Arctic, estimates of 1 to 3 m SOC stocks are based on a geographical subdivision following physiography. This spatial subdivision was chosen because it is expected to reflect different important pedogenic processes occurring across the studied region. Pedons and mapped soil areas in the northern circumpolar permafrost region were separated following physiographic regions of thick and thin sedimentary overburden (Fig. 1; see Heginbottom et al., 1993). Areas of thick sedimentary overburden are described as "areas of lowlands, highlands and intra- and inter-montane depressions characterised by thick overburden, wherein ground ice is expected to be generally fairly extensive" (Heginbottom et al., 1993). Areas of thin sedimentary overburden are described as "areas of mountains, highlands, and plateaus characterised by thin overburden and exposed bedrock, where generally lesser amounts of ground ice are expected to occur" (Heginbottom et al., 1993).

The upscaled SOC stock estimates for the 0 to 0.3 m and 0 to 1 m depth ranges were calculated separately for each soil order, following USDA Soil Taxonomy (Soil Survey Staff, 1999), within the separate NCSCDv2-regions. Permafrost-affected soils (Gelisol soil order) are further differentiated for upscaling into its three suborders: Turbels (cryoturbated permafrost soils), Histels (organic permafrost soils) and Orthels (non-cryoturbated permafrost-affected mineral soils).

For the 1 to 2 m and 2 to 3 m depth ranges, a reduced thematic resolution with aggregated upscaling classes was used. Stocks were calculated separately for the Turbel, Histel and

Orthel suborders of the Gelisol soil order and for the Histosol soils order (organic soils without permafrost). All remaining soil orders were grouped as non-permafrost mineral soils.

The SOC storage (kg C m^{-2}) values for the 0 to 0.3 m and 0 to 1 m depth ranges were based on 1778 individual pedons from around the northern circumpolar permafrost region (mainly from Gelisol and Histosol orders), which have been complemented with SOC data from Batjes (1996) where data for non-permafrost soil orders was missing (this pedon dataset is hereafter called pedon dataset 1). More detailed information regarding this pedon dataset, including details regarding which soil orders were supplemented with information from Batjes (1996), can be found in table S1 of the supplementary online materials. For further details regarding the NCSCD GIS-database and the methods for pedon sampling and calculation of 0 to 0.3 and 0 to 1 m SOC stocks, see Hugelius et al. (2013b). For the deeper soil layers (1 to 2 m and 2 to 3 m depth ranges) a newly compiled pedon database which has been integrated into the NCSCDv2 was used (Fig. 1; Table 1). From this pedon compilation we included 518 pedons that extend down to 2 m and 351 pedons that extend down to 3 m (this pedon dataset is hereafter called pedon dataset 2). Table 1 summarises the number of individual deep pedons available from different geographical regions and areas of thick/thin sedimentary overburden in pedon dataset 2. More detailed information regarding this pedon dataset can be found in table S1 of the supplementary online materials.

2.2 Calculating deltaic SOC stocks

Deltaic SOC stocks in this study are estimated following the methodology that builds on that of Tarnocai et al. (2009) who used data on the mean depth of alluvium, mean delta lake coverage/depth and mean alluvium SOC density (kg C m^{-3}) from the Mackenzie River Delta (Canada) combined with data on the spatial coverage of seven large Arctic river deltas. Here we combined the data used by Tarnocai et al. (2009) with updated information (from scientific literature and databases) on the areal extent of deltas, mean depth of alluvium, delta lake coverage, permafrost extent and segregated ice content in deltaic deposits. The total volume of alluvium for each delta was calculated from the mapped sub-aerial delta extents and the mean depth of alluvial deposits, subtracting the volume that was estimated to be occupied by massive ice and water bodies. To avoid double counting, the top 0 to 3 m of soil were removed from the calculation. In addition, known Yedoma deposits located in the Lena Delta were removed to avoid spatial overlap with estimates for this region. When the total volume of alluvium was calculated, the total SOC stock of each delta was estimated using field data of mean alluvium SOC density (kg C m^{-3}). In all cases, mean values from other deltas were used when there was no direct data for any specific variable in a delta. Table 5 summarises all input data used to estimate deltaic alluvium volume and SOC stocks. More detailed descriptions of calculations are available in the online supplemental material.

2.3 Calculating permafrost SOC stocks in the Yedoma region

For the purpose of these calculations, the Yedoma region was subdivided into areas of intact Yedoma deposits (late Pleistocene ice- and organic-rich silty sediments) and permafrost deposits formed in thaw-lake basins (generalised as thermokarst deposits) which may be either mineral soils, lake sediment or peat deposits. Volumes of unfrozen sediment underlying water bodies and areas covered by deltaic or fluvial sediments were excluded. Twenty-two Yedoma and 10 thermokarst deposit profiles were studied and sampled from river or coastal bluffs exposed by rapid thaw and erosion (Strauss et al., 2013). Total SOC stocks in intact Yedoma and perennially frozen thermokarst deposits below 3 m are calculated based on individual observations of: deposit thickness (n=20 and 8, respectively), organic C content (weight %, n=682 and 219), bulk density (n=428 and 117), and wedge-ice content (volume %, n=10 and 6). The upper 3 m of sediment were excluded to avoid spatial overlap with estimates of storage in 0 to 3 m soils based on the NCSCDv2. For details regarding calculations of the spatial extent of different sediments, data collection and spatial distribution of field observations see Strauss et al. (2013). Because of high inherent (spatial) heterogeneity and non-normal distributed input parameters, the SOC stock calculations are based on bootstrapping techniques using resampled observed values (similar to Strauss et al., 2013). The applied methodology differed from that of Strauss et al. (2013) in several ways. The number of resampling steps for each parameter was connected to the original number of observations of the different parameters deposit thickness, C%, bulk density, and wedge-ice. We did 10,000 separate bootstrapping runs and the total mean SOC stock size estimate was derived afterward for every bootstrapping run. This resulted in an overall mean value calculated from 10,000 observation-based bootstrapping means. Because organic C% and bulk density of individual sediment samples are correlated, paired values were used in the resampling process. Computations were performed using R software (boot package) (R core team, 2012).

2.4 Estimating SOC stock uncertainties

Spatial upscaling using mean values of classes from thematic maps, such as soil maps, builds on the premise that an empirical connection between map classes and the investigated variable can be established through point sampling (Hugelius, 2012). Sources of upscaling uncertainty in such thematic mean upscaling can be divided into database uncertainty arising from insufficient field-data representation to describe natural soil variability within an upscaling class and spatial uncertainties caused by areal misrepresentation of classes in the upscaling map (Hugelius, 2012). Database uncertainty can be estimated based on the standard error (reflects variance and number of independent replicates) and the relative contribution towards the total stock of each upscaling class. This procedure assumes that the available sample is sufficiently replicated to accurately reflect the natural variability within a class. If this is not the case, the uncertainty arising from this so-called representation error can be estimated. Spatial errors in individual upscaling classes can be assessed if dedicated, comprehensive ground truth datasets to assess map accuracy are available, which is not the case in this study. All uncertainty estimates in this study assume that the spatial extent of different soil orders, deltas and the Yedoma region within the northern circumpolar permafrost region are correctly mapped.

Calculations of uncertainty ranges for the different depth ranges and regions of 0 to 3 m soil SOC stocks and deltaic alluvium are based on the methodology described by Hugelius (2012), modified to also include the estimated representation error in those cases where estimates for one region were based on small statistical samples. The uncertainty ranges are 95% confidence interval (CI) ranges calculated from the standard deviation (StD) and proportional areal/volumetric contribution of each upscaling class. The relative contribution to total uncertainty by individual soil classes is defined as the proportion of combined StD and proportional areal/volumetric contribution of that class.

The uncertainty ranges for Yedoma region deposits are the 5^{th} and 95^{th} percentiles of bootstrapped observations (based on the methodology of Strauss et al. (2013)). These ranges are considered equivalent to 95% CI ranges. The uncertainty ranges of the different SOC stock components are combined using a formula for additive error propagation of covarying variables (Roddick, 1987). More detailed descriptions of all calculations, including formulas and a schematic overview of uncertainty calculations (Fig. S1) are available in the online supplemental material.

2.5 Statistical tests of significance

Because different pedon datasets were used to calculate 0 to 1 m SOC stocks (pedon dataset 1) and 1 to 3 m SOC stocks (pedon dataset 2), there was a concern that these two dataset may not accurately reflect the same statistical populations (Hugelius, 2012). Therefore, the circumpolar mean 0 to 1 m SOC storage (kg C m^{-2}) between the two databases was compared using Student's t-test with α=0.05 (test from parameters, software PAST v2.17b; Hammer et al., 2001). These tests were performed at the reduced thematic resolution used to calculate deeper SOC stocks. Because the individual pedon observations and coordinates are no longer available for pedon dataset 1, the tests could not be done separately for the different physiographic regions (mean, standard deviation and n values of pedon dataset 1 for the separate regions are not known).

For each soil upscaling class (at reduced thematic resolution), SOC storage (kg C m^{-2}) in the individual depth ranges (0 to 1 m, 1 to 2 m and 2 to 3 m) were also compared across physiographic regions of thick and thin sedimentary overburden using a two tailed Student's t-test with α=0.05 (software PAST v2.17b).

3 Results

3.1 Mean 0 to 3 m SOC storage and depth distribution in soil classes across regions

3.1.1 Mean pedon SOC storage used for upscaling

Table 2 summarises the SOC storage (kg C m^{-2}) and uncertainty ranges (95% CI) for the different soil classes used in upscaling. More detailed information regarding the databases used to calculate mean SOC storage of different soil upscaling classes in all depth ranges can be found in table S1 of the online supplementary materials. In general, the highest mean SOC storages are in the organic soils (Histosols and Histels), followed by Turbels, Orthels and non-permafrost mineral soils. Organic soils and permafrost-affected soils also store more SOC below 1 m depth (except Orthels in regions of thin sediment overburden). Storage of SOC in poorly developed permafrost soils of the High Arctic is considerably lower than other permafrost soils. Estimates for soils of the High Arctic and physiographic regions of thin sedimentary overburden are associated with wide uncertainty ranges.

The mean SOC storage estimates used for upscaling (Tab. 2) are based on two different pedon datasets (pedon dataset 1 above 1 m depth and dataset 2 for deeper soils). However, both datasets have data for the top meter of soil. These two pedon datasets represent independent samples for estimating SOC storage (kg C m^{-2}) in the top meter of soils in the northern circumpolar permafrost region. If both datasets are assumed to be unbiased, representative samples of SOC storage, they should provide similar estimates. Therefore, inter-comparisons of these estimates are informative. Comparing the 0 to 1 m SOC storage (kg C m^{-2}) values from the two pedon datasets region revealed that there are no significant differences between the datasets for mean 0 to 1 m SOC storage (based on all circumpolar pedons) in the Orthel and Histel classes (t-test, $p>0.05$). Turbels and non-permafrost mineral soils have significantly higher SOC in pedon dataset 2 (t-test, $p<0.05$). Histosols have significantly lower SOC in pedon dataset 2 (t-test, $p<0.05$).

3.1.2 Comparison of SOC storage across regions and depths

Pedon dataset 1 has no data below 1 m depth and for consistency in comparisons only pedon dataset 2 is referred to regarding all descriptions or comparisons of SOC storage across regions or depth distribution of SOC within soil classes. The vertical distribution of SOC through the profile varies greatly between soil orders (Fig. 2). In most soil classes the upper 1 m of soil stores more SOC than the deeper depth ranges but for Histosols, the highest estimated SOC storage is in the 1 to 2 m depth range (Figs. 2G and 2H). In Orthels in regions of thin sediment overburden, non-permafrost mineral soils and soils of the High Arctic a large fraction (30% to 50%) of total 0 to 3 m SOC is stored in the top-soil (upper 0.3 m; Figs. 2E, 2I, 2J and 2K). Outside of the High Arctic, organic soils, Turbels and Orthels in thick sediment regions store ~50% or more of SOC below 1 m depth.

Statistical comparison of SOC storage between physiographic regions of thick and thin sediment overburden shows significantly higher SOC in thick sediment regions across all depth ranges for Orthels and for non-permafrost mineral soils in 2 to 3 m depth (Figs. 2E, 2F, 2I and 2J; t-test, $p<0.05$). At depths down to 2 m, Histosol SOC storage is significantly higher in thin sediment regions (Figs. 2G and 2H; t-test, $p<0.05$). Other soil upscaling classes show no significant differences between physiographic regions.

3.2 Upscaled soil area and SOC stocks across regions

The estimated soil area of the northern circumpolar permafrost region is 17.8×10^6 km^2 (excluding exposed bedrock, glaciers and ice-sheets and water bodies). This also includes the full areal extent of regions where permafrost coverage is non-continuous so that a significant fraction of the area is not in permafrost terrain. Physiographic regions with thick sedimentary overburden occupy 35% and regions with thin sedimentary overburden 65% of the soil area

(Table 3). The North American continent (including Greenland) accounts for 39% of the soil area and Eurasia for 61% of the soil area.

Total estimated northern circumpolar permafrost region SOC stocks (±95% CI) are 217±12 Pg for the 0 to 0.3 m depth and 472±27 Pg for the 0 to 1 m depth (Tables 3). Estimated deeper SOC stocks are 355±81 Pg for the 1 to 2 m depth and 207±42 Pg for the 2 to 3 m depth (Table 2). The summarised SOC stocks for 0 to 2 m depth are 827±108 Pg and for 0 to 3 m depth are 1034±150 Pg.

Thick sediment areas have lower total SOC stocks than thin sediment areas in the 0 to 0.3 m, 0 to 1 m and 1 to 2 m depth ranges (corresponding to a significantly smaller areal coverage). However, in the 2 to 3 m depth range the total SOC stocks are higher in areas of thick sediments, reflecting the very low estimated SOC contents below 2 m depth for some soil classes which have significant areal extent in thin sediment regions (i.e. Orthels and non-permafrost mineral soils; Fig. 2 and Tab. S1). There is a clear trend of wider uncertainty ranges in thin sediment regions, caused by variable mean SOC storage (Fig. 2) and a low number of available pedons for this very large region (Tab. 1). Maps of estimated SOC content (Fig. 3) show clear differences in estimated SOC stocks, with higher numbers in thick sediment regions than in the thin sediment regions.

The High Arctic region occupies 6% of the northern circumpolar permafrost region and stores an estimated 34±16 Pg SOC in the 0 to 3 m depth range (3% of total permafrost region 0 to 3 m SOC stocks). Most of this is in the upper meter of the soil with 10±3 and 24±8 Pg SOC in the 0 to 0.3 m and 0 to 1 m depth ranges, respectively. Estimates of SOC stocks in deeper soil layers in the High Arctic are lower, 7±5 and 3±3 Pg SOC in the 1 to 2 m and 2 to 3 m depth ranges, respectively.

Permafrost-affected soils dominate SOC storage in the permafrost region with 70% of total stocks (Table 4). Turbels outside of the High Arctic region, which account for 31% of the soil area, store 41% of total 0 to 3 m SOC stocks (Table 4), and is the single dominant upscaling class across all depth ranges and regions (Table S1). In the 1 to 2 m depth range, the organic soils (Histels and Histosols) contribute more to the total SOC stocks, due to higher mean SOC storage in that depth interval (Fig. 2). Histosols are especially important in regions of thick sedimentary overburden where the mean depth of peat deposits (data not shown) and mean SOC stocks are greater. Outside of continuous permafrost covergae, non-permafrost mineral soils cover 38% of the northern circumpolar permafrost region, but accounts for only 15% of the SOC mass.

Estimates for permafrost soils are the most uncertain. For the 0 to 1 m SOC stock estimate, Turbels, Orthels and Histels together account for 89% of the total estimated uncertainty (61%, 14% and 15% respectively). At greater depths, uncertainties increase further. Overall, the Turbels introduces the most uncertainty to the SOC stock estimates across depth ranges, especially at depths below 1 m. Turbels account for 54% to 89% and 72% to 90% of upscaling uncertainty (1 to 2 m and 2 to 3 m depth ranges, respectively). The particularly large uncertainties of Turbel SOC storage estimates in physiographic regions of thin sedimentary overburden are caused by few available pedons that show large within-class variability. The relative uncertainties of High Arctic soil SOC stocks are large. However, these soils have low SOC stocks (0.2 to 4% of total permafrost region SOC stocks across upscaling regions and depth ranges) and contribute little towards the uncertainty of the total estimates. More detailed information regarding the total soil area, SOC stocks and relative contribution towards the estimated uncertainty ranges of different soil upscaling classes in all depth ranges can be found in table S1 of the online supplementary materials.

3.3 SOC stocks below 3 m depth in deltaic deposits

Table 5 summarises data sources, the different parameters used to estimate the volume and SOC content of deltaic alluvium and calculated results for the individual deltas. The total estimated area of major river deltas in the northern circumpolar permafrost region is 75,800 km^2. This estimate includes twelve deltas ranging in size from 500 to 32,000 km^2. The combined estimated alluvium volume below 3 m depth in these deltas is ca. 3,500 km^3 (stored between 3 and 60 m depth, mean alluvium depth is 54 m). Field-based observations of alluvium depth are very limited and estimates are based on only one observation for the Lena River Delta and five different observations for the Mackenzie River Delta. Estimates for mean alluvium SOC density are available from the literature for five different delta units and range from 8.3 to 56.2 kg C m^{-3}. For deltas where no direct observations are available, alluvium depth and SOC content is estimated from the mean values of those deltas that have data.

Estimated SOC stocks in deltaic alluvium below 3 m depth are 91±52 Pg. Because of high mean alluvium SOC density total stocks in the Mackenzie River Delta (34 Pg) are higher than those of the Lena River Delta (23 Pg), which is considerably larger and accounts for 44% of the total estimated volume of alluvium. The Yana River Delta stores an estimated 7 Pg and alluvial deposits of the remaining nine deltas store the remaining 27 Pg (≤ 5 Pg each). Between 51 and 92% (mean 84%) of deltaic alluvium is stored in permafrost. Estimated SOC stocks in perennially frozen alluvium are 69±38 Pg. For most of the deltas included in this estimate, no field-observations of alluvium depth or SOC content are available. Calculated CI intervals indicate that uncertainties arising from limited observations of alluvium depth (±49 Pg) are greater than uncertainties from poorly estimated alluvium SOC density (±18 Pg).

3.4 Storage of permafrost SOC in the Yedoma region

The combined area of the Yedoma core region in Siberia (Romanovskii, 1993) and Alaska (Jorgenson et al., 2008) is 1,387,000 km^2. Of this 416,000 km^2 (30%) is considered intact Yedoma and 775,000 km^2 (56%) is comprised of permafrost deposits that have previously gone through thermokarst cycling (refrozen sediments accumulated in thaw-lake basins, including mineral soil, lake sediment or peat deposits) (Grosse et al., 2013; Strauss et al., 2013). Within this Yedoma core region, thawed sediments underlying lakes and rivers (150,000 km^2) and areas covered by deltaic or fluvial sediments (47,000 km^2) are excluded from calculations.

The estimated stocks of permafrost SOC below 3 m depth in the Yedoma region is 181 Pg with an uncertainty range of 130 to 239 Pg (hereafter approximated to ±54 Pg). Of this an estimated 74 Pg with an uncertainty range of 55 to 94 Pg (hereafter approximated to ±20 Pg) is stored in intact Yedoma while 107 with an uncertainty range of 60 to 161 Pg (hereafter approximated to ±50 Pg) is stored in perennially frozen thermokarst basin deposits.

The estimated total stocks of permafrost SOC in the Yedoma region is 213 Pg with an uncertainty range of 164 to 267 Pg (hereafter approximated to ±52 Pg). Of this an estimated 83 Pg with an uncertainty range of 64 to 104 Pg (hereafter approximated to ±20 Pg) is stored in intact Yedoma while 130 Pg with an uncertainty range of 85 to 180 Pg (hereafter approximated to ±45 Pg) is stored in perennially frozen thermokarst basin deposits.

4 Discussion

This study presents updated estimates of SOC stocks in the northern circumpolar permafrost region based on markedly improved databases. The study includes the first spatially distributed quantification of 1 to 3 m SOC stocks as well as the first quantitative uncertainty ranges for SOC stocks in this region. In recognition of the limited soil development in high latitude areas with thin sediments, the High Arctic region was treated separately in upscaling. Adding up SOC stocks in 0 to 3 m soils, deltaic deposits and Yedoma region permafrost deposits for the northern circumpolar permafrost region results in an estimate of 1307 Pg with an uncertainty range of 1140 to 1476 Pg (roughly ±170 Pg). Of this, 999 Pg of SOC is stored in permafrost terrain (defined as storage in Gelisols/High Arctic soils and in deposits below 3 m depth). The SOC stock in perennially frozen soil and sediment is estimated to be 822 Pg (or 63%) or less (assuming an active layer depth of 30 cm or more in all Gelisols and High Arctic soils).

4.1 Differences to previous estimates

The scope of this estimate is similar to the previous depth-integrated estimate of permafrost region SOC stocks by Tarnocai et al. (2009). Revised databases and methodology lead to substantial reductions of estimated total SOC stocks (Tab. 6), especially below 3 m depth. There is a considerable reduction in estimates of SOC stored in permafrost terrain and in permafrost.

The updated estimates of northern circumpolar permafrost region SOC stocks in 0 to 0.3 m and 0 to 1 m depth are largely based on the same data as the equivalent estimates of Tarnocai et al. (2009). Differences between estimates (+26 Pg and −24 Pg, respectively) are due to gap-filling procedures and updating of the NCSCD spatial framework (see Hugelius et al., 2013a, 2013b) and to new SOC estimates for the High Arctic region. The updated pedon database used to estimate SOC between 1 and 3 m depth includes spatial representation across the northern circumpolar permafrost region and about a ten-fold increase in the number of pedons compared to that of Tarnocai et al. (2009). While the relative changes in the total 0 to 3 m SOC stocks are small, there are considerable differences between individual soil orders. The revised estimates are considerably lower for Turbels and Histels but higher for Orthels, Histosols and non-permafrost mineral soils (Tab. 6). This results in a 120 Pg reduction of SOC stored in permafrost in the 0 to 3 m depth range compared to the previous estimate. Note that the estimates of the fraction of SOC stored in permafrost are highly uncertain as they are based on an assumption that the average active layer depth in all Gelisols is 0.3 m or more (see Kuhry et al., 2013).

Using a subset of pedon dataset 2 and soil (sub)order coverage from the NCSCD, Harden et al. (2012) estimated total northern Gelisol SOC stocks to be 1060 Pg, compared to 727 Pg in this estimate. The major cause for this difference is that Harden et al. (2012) does not subdivide the upscaling following physiographic regions, which leads to higher estimated mean SOC storage in Gelisol soil orders for regions of thin sedimentary overburden.

In recognition of the limited soil development in high latitude areas with thin sediments, the High Arctic region was treated separately in upscaling. A previous study estimated active layer SOC stocks for this region to be 12 Pg (Horwath Burnham and Sletten, 2010), which falls within current SOC estimates of 10±3 Pg and 24±8 Pg in the 0 to 0.3 m and 0 to 1 m depth ranges, respectively.

The previous estimate of deltaic SOC stocks by Tarnocai et al. (2009) was extrapolated based on field data from the Mackenzie River Delta only. The revised, substantially lower, estimate presented here builds on this same basic methodology but with some additional sources of data from the literature. The difference between estimates is mainly caused by lower estimates of mean alluvium SOC density (kg C m^{-3}) when including new available data from the Colville and Lena river deltas (Ping et al., 2011; Schirrmeister et al., 2011b; Zubrzycki et al., 2013). There are smaller differences in the estimated total volume of deltaic alluvium. This is calculated based on areal extent and depth of alluvium, accounting for the volume of water bodies (assuming a mean water depth of 5 m) and volumetric massive ice content. While the areal extent of deltas for the updated estimate is based on an entirely different source (Walker, 1998) and includes a larger subset of individual deltas, the difference in total estimated sub-aerial delta surfaces is relatively small. The estimated depth of alluvium in deltas is also similar to the original estimate. Tarnocai et al. (2009) consider all deltaic alluvium below 3 m to be in permafrost and do not consider any reduced alluvium volume caused by occurrences of massive ice. If no massive ice content is assumed in this study, the equivalent estimate would increase from 91±52 Pg to 98±54 Pg.

The updated estimate of permafrost SOC storage below 3 m depth in the Yedoma region is based on the same dataset as the estimate for the total permafrost SOC stocks in this region developed by Strauss et al. (2013). Removing depth overlap with the 0 to 3 m soil estimate resulted in a reduction from 213 Pg to 181 Pg. The substantial reduction compared to the previous depth-integrated estimate by Tarnocai et al. (2009) is mainly caused by a twofold reduction of estimated bulk density, a reduction of estimated deposit thickness, and different assumptions regarding the characteristics of intact Yedoma compared to refrozen thermokarst sediments (see Fig. 3 in Strauss et al. 2013).

4.2 Distribution patterns of SOC stored in 0 to 3 m soil

4.2.1 SOC distribution by regions

When compiling pedon dataset 2 for upscaling of SOC stocks in the 1 to 3 m depth range Hugelius et al. (2013a) subdivided pedons and upscaled SOC stocks based on a continental subdivision (North America vs. Eurasia) as opposed to the upscaling based on physiographic regions used in this study. A first version of this study included both continental and physiographic upscaling (Hugelius et al., 2014). This study is based only on physiographic upscaling as we argue that this approach reflects a more accurate assessment of SOC distribution than subdivision by continent. The physiographic regions reflect differences between upland and lowland areas across the northern circumpolar permafrost region (Heginbottom et al., 1993) and are better suited to reflect different soil types and important pedogenic processes. This is also consistent with other studies that have utilised physiography and its influence on soil drainage to upscale soil properties (Harden et al., 2003; Yi et al., 2009). A map of mean SOC storage (Fig. 3) upscaled using physiography shows important patterns that were lacking in continent based upscaling (Hugelius et al., 2014). For example, in the 1 to 2 m depth range, mountainous regions in Siberia emerge as having low SOC stocks below 1 m. This estimate upscaled based on physiographic regions reflects differences between upland and lowland areas across the northern circumpolar permafrost region (Heginbottom et al., 1993). In thin sediment areas ("areas of mountains, highlands, and plateaus characterised by thin overburden and exposed bedrock") we would generally expect conditions to be less favourable for accumulation of large SOC stocks than in areas of thick sediment overburden ("areas of lowlands, highlands and intra- and inter-montane depressions characterised by thick overburden"). The overall upscaled SOC stock estimates follows this pattern of higher stocks in thick sediment areas, but some individual soils classes do not. Our estimates for thin sediment areas are characterised by large variability, poor pedon representation, and wide uncertainty ranges (see 4.3.1 below). We emphasise that this dichotomous subdivision into two distinct physiographic landscape types is not realistic at a local scale where transitions are more discrete. For studies at finer scales we would not recommend the use of this relatively coarse subdivision.

4.2.2 SOC distribution by soil types

In general, the permafrost soils and organic soils dominate 0 to 3 m SOC storage in the northern circumpolar permafrost region, especially at depths >1 m. This is in accordance with previous results from this region (e.g. Ping et al., 2008; Tarnocai et al., 2009) and reflects current understanding of the processes that lead to accumulation of SOC in permafrost region soils (cryoturbation, accumulation of peat and repeated deposition and stabilization of organic-rich material).

Because of their substantial areal extent and high mean SOC storage (kg C m^{-2}), cryoturbated mineral soils are important SOC reservoirs. Turbels south of the High Arctic region store 41% of SOC stocks with 31% areal coverage (Tab. 4). There are no significant differences in mean SOC storage between physiographic regions of thick and thin sedimentary overburden regions but there is notable variability in the data at all depths. Especially in areas of thin sediment overburden, low data availability (Tab. 1) combined with great natural variability leads to wider relative uncertainty ranges of estimates.

The mean SOC storage (kg C m^{-2}) is highest in organic soils (Histosols and Histels; Tab. 2), and these soils also contribute greatly to total SOC stocks (both classes store 14% each of 0 to 3 m SOC stocks with only 5% and 7% areal coverage, respectively). Regions dominated by organic soils, such as the West Siberian Lowlands or the lower Mackenzie River basin, are especially SOC-rich across depths (Fig. 3). There is relatively large variability in SOC storage of organic soils across regions. Unexpectedly, the upper 2 m of Histosols in regions of thin sediment overburden have significantly higher SOC storage than Histosols from thick sediment areas (Fig. 2). Considering the low degree of replication for Histosols in areas of thin sediment overburden (n=8), additional field observations are needed to further evaluate this result. This high estimated mean SOC storage of Histosols in thin sediment regions is heavily influenced by a few very SOC-rich pedons and should be interpreted with caution.

Mineral permafrost soils unaffected by cryoturbation (Orthels) differ greatly across regions. In areas with recurring deposition and stabilization of organic-rich sediment (alluvium, proluvium, colluvium or wind-blown deposits) very large SOC stocks have accumulated over long timescales (Schirrmeister et al., 2011). In other cases, shallow, non-cryoturbated permafrost soils in e.g. mountain regions store little SOC (Ping et al., 1998). In this study, Orthels in regions with thin sediments (corresponding to upland or montane areas) store little

SOC while Orthels in regions with thick sediment have accumulated significant SOC stocks down to 3 m depth (Fig. 2).

In regions of discontinuous permafrost cover (commonly in areas of boreal forest), a large portion of the landscape is covered by non-permafrost mineral soils which also store significant amounts of SOC. Non-permafrost mineral soils cover 38% of the total permafrost region area and stores 15% of total 0 to 3 m SOC stocks. In the upper meter, upscaling is based on the eleven different non-permafrost mineral soil orders mapped in the NCSCDv2. Estimated mean SOC storage in this depth interval shows significant variability in estimates with a range from 1.7 to 25.2 kg C m^{-2} (Tab. 2). In the 1 to 2 m depth interval estimated SOC storage is ~10 kg C m^{-2} in both thick and thin sediment regions. This remains unchanged below 2 m in thick sediment regions while there is significantly less SOC in thin sediment regions. A large fraction of SOC in these latter soils is stored in the top-soil within O and A horizons where high SOC storage may indicate accumulation of humified organic matter, charcoal, or char-mediated sorption in fire-prone boreal forests. Beneath O and A soil horizons, important mechanisms for stabilizing SOC in permafrost free mineral soils include deep rooting, sorption of leached dissolved organic C to clay particles or formation of complexes with iron and/or aluminium. Lower SOC storage in deeper horizons reflects that these soils are less affected by C stabilization processes such as cryoturbation or repeated deposition typically found in permafrost or organic soils. The very low storage in non-permafrost mineral soils of region with thin sediments is due to influence from pedons in alpine terrain with limited soil development where bedrock is typically encountered within the upper 3 m.

4.3 Estimated uncertainties and data gaps

This study presents the first quantitative uncertainty ranges for estimates of SOC stocks in northern circumpolar permafrost region. The widest uncertainty ranges are associated with those same components that also Tarnocai et al (2009) identified as being most uncertain. That study assigned low to very low confidence for estimates of SOC stocks stored in deep soil (1 to 3 m), Yedoma region deposits and deltaic deposits.

For 0 to 3 m soils and deltaic deposits the uncertainty ranges were calculated based on within class variability of pedons (or alluvial deposit thickness) and areal/volumetric coverage of classes. For Yedoma region SOC stocks, the uncertainty ranges correspond to the 5th and 95th

percentiles of bootstrapped estimates. The former approach integrates all individual soil-horizons to the pedon level and assumes a (log)normal data distribution while the latter allows non-normality, but also differs in that it does not integrate individual sediment layers or horizons at the site/pedon level. These updated estimates are based on collaborative databases where efforts have been made to collect data from across regions and from different research groups. Despite this, substantial regional data gaps remain such as in the High Arctic, central Siberia and many river deltas.

4.3.1 Spatial distribution of pedons

The spatial distribution of pedons used to estimate SOC stocks in the 1 to 3 m depth range is highly clustered (Fig. 1). For example, parts of Alaska and western Russia are well represented, but there are significant data gaps in Central Asia, Scandinavia, Greenland, Svalbard and Eastern Canada. There is a clear possibility that the available pedons are not truly representative for those areas where field data are lacking. This source of uncertainty is not addressed in this study but we acknowledge that adding more field-based data from under-sampled regions could substantially improve estimates. A previous comparisons between estimates of 0 to 1 m SOC stocks based on the NCSCD and local scale studies revealed pronounced differences, especially for Turbels and organic soils (Kuhry et al., 2010). A way to potentially address this source of uncertainty in future studies is to assess the upscaled estimates against independent validation datasets. Such approaches could be applied across scale to address uncertainties from site-scale to regional scales.

4.3.2 Regional uncertainties of estimates for 0 to 3 m soils

The estimates of SOC stocks in 1 to 3 m soils are based on a highly generalised upscaling scheme. Pedons are grouped based on soil characteristics (defined by absence/presence of permafrost, thick organic layers and cryoturbation) and mean SOC storage values are then assigned to large geographical regions (physiographic regions of thick/thin sediments, respectively). For the estimate of 0 to 1 m soils, a similar simplified scheme was applied to all NCSCD regions except Alaska and Canada (Tarnocai et al., 2009). In Alaska and Canada, SOC storage values were individually assigned to mapped soil series (Alaska) or soil names (Canada) from national soil inventories. Because of these methodological differences, there are some discrepancies across depths for estimates in Alaska and Canada, where 1 to 2 m or 2 to 3 m soil layers are sometimes estimated to hold more SOC than the upper meter of soils.

This applies to some areas in the western Hudson Bay Lowlands and parts of the Canadian Arctic archipelago outside of the High Arctic zone. Clear trends of decreased SOC storage with depth (Fig. 2) indicate that these vertical patterns in SOC storage are not realistic.

The upscaling approach applied here relies on the assumption that our pedon datasets are accurate and unbiased samples of permafrost region soils (Hugelius, 2012). For some regions, the degree of replication in individual soil classes is very low (Table 1). To correct for potential errors arising from incomplete sample representation in regions of thin sedimentary overburden and the High Arctic region the representation error was estimated and included in the summative uncertainty ranges. The representation error of any class in an under-sampled region is estimated by extracting the variability from repeated subsampling of larger samples available from other regions. For example, we thus assume that Turbels in thick sediment regions are roughly equally variable as Turbels in thin sediment regions.

In the High Arctic region, there is very limited pedon data available and the current estimate is based on only eight pedons (six Orthels, one Histel and one Turbel), which were grouped together as Gelisols for calculations. Because of low SOC stocks, this region does not contribute much to the overall uncertainty of total estimates. However, due to the very limited field data and the large degree of generalization in some High Arctic soil maps (e.g. Svalbard and Greenland, see Hugelius et al., 2013b) these estimates must be regarded as preliminary and highly uncertain. Storage of SOC in cryoturbated and organic soils is often highly variable, and sample sizes of at least >30 is recommended (Hugelius, 2012). In the current estimate of SOC below 1 m depth, there is very poor representation of Turbels for thin sediment regions outside of the High Arctic (n=6 and 2 for the 1 to 2 m and 2 to 3 m depths, respectively). Based on currently available data, we cannot provide robust estimates of SOC storage in physiographic regions of thin sedimentary overburden or the High Arctic region. This is also reflected in wide uncertainty ranges for SOC stocks in these regions. Considering their large areal extent it is nevertheless important to provide assessments based on what little data are available. Further field sampling and/or data compilation will hopefully provide opportunities to refine these estimates.

4.3.3 Differences between soil pedon databases and sampling biases

For the 0 to 1 m depth interval, two independent sources of pedon data to estimate SOC storage (kg C m^{-2}) are available (pedon dataset 1 used to calculate 0 to 1 m SOC stocks and pedon dataset 2 used to calculate 1 to 3 m SOC stocks). While pedon dataset 2 was not actually used in the quantification of 0 to 1 m SOC stocks, estimates are available for that depth range. If we assume that the two independent datasets are accurate samples of 0 to 1 m SOC stocks, there should be no significant differences between the datasets. We therefore infer that the significant differences in 0 to 1 m SOC storage between pedon datasets v1 and v2 could be an indication of sampling biases. Near surface pedon SOC storage is correlated to SOC storage below 1 m depth (Hugelius et al., 2014) and any biases in 0 to 1 m SOC could therefore also affect our estimates for stocks below 1 m depth. Summarised for the whole permafrost region, there are no significant differences between the datasets for the Orthel and Histel classes, while Turbels and non-permafrost mineral soils may be biased high and Histosols biased low in pedon dataset 2. Because data for pedon dataset 1 is only available aggregated to the whole permafrost region, no statistical comparisons can be made at regional levels. Detailed comparisons reveal that in North America, pedon dataset 2 is consistently estimating higher values than pedon dataset 1 (data not shown). In other regions, there are no clear patterns and results differ across soil classes.

There is an indicated bias towards high SOC in Turbels of pedon dataset 2. Closer examination of regional patterns reveals that this is largely due to very high SOC storage for Turbels in North America (at all depths). For Eurasian Turbels the pattern is opposite with higher estimates in pedon dataset 1. When subdivided following physiographic regions differences between the two datasets are small. The bulk of available North American Turbels are from the North Slope of Alaska (Fig. 1), where previous studies have also shown high mean SOC storage in cryoturbated soils (Michaelson et al., 1996; Ping et al., 1998; Johnson et al., 2011). In general, the available data in pedon dataset 2 is geographically clustered (Fig. 1; Hugelius et al., 2013a) and more dispersed samples of pedons from across regions could reduce any biases introduced by clustered sampling.

Hugelius et al. (2013a) discuss a potential large bias for organic soils where targeted sampling campaigns may cause sites with thick peat deposits to be overrepresented in datasets. To avoid such a bias, pedon dataset 2 includes all sites with organic soils, even if data from the mineral subsoil was missing (data from mineral C-horizons below organic deposits were extrapolated to full depth or default values were applied). A closer examination of the available data on peat deposit thickness reveals that the peat depths in those sites, where no extrapolation was needed (i.e. where coring was pursued to great depths in the field), are not representative of the true depth distribution of peat deposits based on all available observations from organic soils. If only pedons without extrapolation are used, mean peat depths are overestimated by a factor 2 (Fig. 4). If only sites without extrapolation were used to calculate SOC stocks, the total SOC stock estimates for organic soils (Histosols and Histels) would increase from the current 302 Pg to 338 Pg. The estimated error introduced by applying default values is on the order of only ±2 Pg (calculated from the standard error of means of the applied default values and mean extrapolation depth of pedons). The use of sites where data on mineral sub-soils was extrapolated may be one factor contributing to the indicated low-bias of Histosols in pedon dataset 2 when compared to pedon dataset 1.

It is difficult to assess the potential bias between pedon datasets v1 and v2 for non-permafrost mineral soils. There is a much larger replication for these soils in pedon dataset 1. However, estimated SOC storage for many pedons in dataset v1 are from the global scale ISRIC database (Batjes, 1996; Tab. S1) including all Eurasian permafrost-free soils and North American Aridisols, Andisols and Ultisols. Because of this, the data used for much of the non-permafrost mineral soils in dataset v1 are likely not truly representative of soils in the permafrost region.

4.3.4 Data availability and uncertainty estimates for deltaic deposits

The updated estimate of deltaic SOC storage confirms that a substantial stock of permafrost SOC is stored in these deposits, but it is also clear that more field observations are needed to produce robust estimates. The calculated CI ranges indicate that uncertainties are larger concerning alluvium depth than mean SOC storage value, but the observational base for both estimates are very small and from most major deltas no field observations are available (Tab. 5). The estimated uncertainty ranges include an approximation of representation errors caused by the limited sample sizes. However, these estimates cannot fully account for the fact that most deltas lack field data altogether. Because of these very limited databases these estimates must be considered as preliminary for those deltas where no data is available. Further, the estimates rely on the assumption that alluvial SOC contents measured in the near surface can be extrapolated to full depth and the reported uncertainty ranges assume a correct spatial extent of deltas and correct volumetric extent of water bodies and massive ice.

4.3.5 Uncertainties and data gaps of estimates for Yedoma region deposits

SOC stocks in intact Yedoma and perennially frozen thermokarst deposits are calculated based on bootstrapped analyses of data on deposit thickness, organic C %, bulk density (including segregated ice %), and wedge-ice volume gathered from a total of twenty-two study areas sampled/described in the field. This approach reflects the variability of individual observations (i.e. analyses of discrete sediment samples or individual depth measurements), which is an effective way of estimating stocks with large inherent (spatial) variability. By estimating 1 mean based on 10,000 single observation-based bootstrapping means, our single estimator's uncertainty is remarkably lower compared to Strauss et al. (2013). To further improve SOC stock calculation, sensitivity analysis revealed that enhanced data on ice wedge volume (Ulrich et al., 2014) and Yedoma deposit thickness will reduce uncertainties significantly.

Another potential source of uncertainty is the geographical extent of the Yedoma region, which is challenging to define discretely. As described in Strauss et al. (2013), the definition of the Yedoma region used here is based on estimates from Romanovskii (1993) for Siberia and Jorgenson et al. (2008) for Alaska. Moreover, we added ~65,000 km² for regions with smaller known Yedoma occurrences (e.g. south of Taymyr Peninsula and Chukotka in Russia and the Yukon Territory in Canada). To describe the spatial fragmentation of Yedoma deposit remnants, we used a fragmented Yedoma coverage in the region of 30%, whereas thermokarst basins with refrozen sediments cover 56%. Existing thermokarst lakes and rivers were excluded, covering 14% of the region. To improve this simplified approach, an uncertainty reduction could be reached by implementing spatially explicit data of intact Yedoma distribution based on geological maps for Siberia (Grosse et al., 2013). Nevertheless, data for thermokarst deposit coverage and intact Yedoma coverage in the Taymyr lowlands, Chukotka, parts of Alaska and north-western Canada are currently not available.

4.3.6 Potential error sources not included in uncertainty estimates

The uncertainty ranges calculated for this study are based on the assumption that the various areal extents of soil (sub)orders, deltas, intact Yedoma and thermokarst are correctly mapped. In all cases we thus assume that the maps are right and that spatial errors do not contribute to estimated uncertainties. A regional study of the Northern Usa River Basin (Russian Arctic) showed that uncertainties from map errors were similar in magnitude as uncertainties from insufficient pedon representation or natural variability (95% CI ranges both estimated at ±8% for 0 to 1 m SOC stocks; Hugelius, 2012). Because no dedicated ground-truthing dataset is available to assess the NCSCD soil maps that form the spatial base of upscaling SOC in 0 to 3 m soils, we cannot directly quantify this error. Small scale maps (covering large geographic regions) do not necessarily have lower mapping accuracy than large scale maps (covering small geographic regions), but because of the necessary generalization inherent in map-making, large scale maps from local studies (such as the land cover maps used by Hugelius, 2012) are expected to have higher mapping precision. We would thus expect that uncertainty from spatial errors in the maps used in this study to be equal to or greater than those found for the Northern Usa River Basin (i.e. a 95% CI of ±8% or more). If we assume an uncertainty of ±10% from spatial error component in all estimates, the propagated uncertainty range of the combined estimate of 1307 Pg SOC would increase by ~±30 Pg to ~±200 Pg. However, to properly assess the spatial errors in permafrost region SOC stock estimates, comprehensive ground-truthing datasets for circumpolar soil classification maps, deltaic extent and Yedoma region extent are needed.

Imprecision in field or laboratory measurements (e.g., sample volume, bulk density or C content) are not accounted for in this study. The relative importance of such errors is expected to differ between different studies, scales and landscape types. Goidts et al. (2009) provide a comprehensive analysis and discussion of different sources of uncertainty in SOC stock estimates and their propagation in upscaling. They conclude that following upscaling to landscape scale, imprecision in laboratory measurements of rock mass fragments (>2 mm), SOC concentration (%) and bulk density may propagate and cause substantial uncertainty in estimates. However, as this circumpolar estimate study combines field and laboratory data collected from a multitude of different sources over several decades, quantifying this uncertainty is currently not possible.

4.4 Deposits with significant SOC stocks below 3 m depth

This estimate of SOC stocks in the northern circumpolar permafrost region includes 0 to 3 m soils as well as deeper deltaic deposits and permafrost deposits in the Yedoma region. Other deposits with significant SOC stocks below 3 m depth have not been included. In many organic soils of the permafrost region, peat deposits extend below 3 m depth (e.g. Sheng et al., 2004; Tarnocai et al., 2005; Hugelius and Kuhry, 2009; Yu, 2012). Of the organic soils included in pedon dataset 2 in this study, 17% sites have peat deposits extending below 3 m depth (Fig. 4) and these peat deposits are expected to store substantial SOC stocks in addition to what is included here.

The current estimate for deltaic deposits includes the twelve major deltas in the permafrost region (selection based on Walker, 1998), but all intermediate or small deltas are excluded. Presently, there is no dataset summarizing the aerial extent of deltaic deposits in the northern circumpolar permafrost region, but a geospatial characterization of Arctic permafrost coastlines (Lantuit et al., 2012) shows significant occurrences of deltas along the Arctic coastline besides those included here. New data also reveals that, besides deltas and the Yedoma region, there are significant SOC stocks in other unconsolidated deeper Quaternary deposits of the permafrost region (Hugelius et al., 2011; Schirrmeister et al., 2011a; Ping et al., 2011; among others). Following the physiographic subdivision, 6.2×10^6 km^2 of the permafrost region is characterised by thick sedimentary overburden (sediments deeper than 5 to 10 m; Brown et al., 2002). Deltaic deposits and the Yedoma region included in this study together cover ca. 1.5×10^6 km^2. Any SOC stored in deposits below 3 m depth in the remaining ca. 5×10^6 km^2 of thick sedimentary overburden remains unaccounted for.

4.5 Potential vulnerability and remobilization of permafrost region SOC stocks

The substantial SOC stocks of the northern permafrost region are vulnerable to thaw remobilization following permafrost degradation (Schuur et al., 2008, 2013). Key processes of permafrost degradation include active layer deepening, talik or thermokarst formation and thermal erosion (Schuur et al., 2008; Grosse et al., 2011). While active layer deepening mainly affects near surface soils (Harden et al., 2012), taliks, thermokarst and thermal erosion can cause remobilization and potential mineralization of SOC stored at greater depths. Local scale studies indicate that both active layer deepening and thermokarst (or thermoerosion) can affect substantial fractions of permafrost landscapes over decadal timescales (Jones et al., 2011; Hugelius et al., 2011, 2012; Sannel and Kuhry, 2011; Jones et al., 2013).

Both active layer SOC and permafrost is highly susceptible to impacts from wildfire (Harden et al., 2000), which has increased in severity and areal extent with recent warming (Turetsky et al., 2011). SOC stocks in the permafrost region may be reduced directly via combustion, or indirectly due to post-fire increases in soil temperature and decomposition (Harden et al., 2006; Mack et al., 2011). Fire-driven reductions in organic-horizon thickness also decreases sub-soil insulation and cause active layer deepening, which can increase the amount of SOM susceptibly to decomposition in the unfrozen phase (O'Donnell et al., 2011).

Global scale projections of greenhouse-gas emissions from permafrost deposits using Earth System Models (ESMs) demonstrate that inclusion of permafrost soil C stocks lead to the potential for a large positive climate feedback from the permafrost region (Koven et al., 2011; Schaefer et al., 2011; Burke et al., 2012; Schneider von Deimling et al., 2012; MacDougall et al., 2012). These models are still simplified representations of permafrost carbon cycling and do not resolve high landscape spatial heterogeneity or account for many observed processes, such as thermokarst or post-fire dynamics. The complexity of ESMs also makes it difficult to assign mechanistic sources of model errors. In order to increase confidence in ESMs, it is necessary to better understand the controls on soil C by process, location, and depth so that observations can be used as a benchmark for these models. Extant ESM-based quantifications of the permafrost-climate feedback have not included SOC stocks of deltaic alluvium or Yedoma and the reduced estimates for these stocks would not affect published projected feedback magnitudes. Using a simplified modelling framework, Burke et al. (2012) demonstrated that uncertainties in quantification of permafrost SOC stocks accounted for ca. half of the variability in ESM projections of increased global mean temperature associated with permafrost carbon thaw (excluding variability caused by different representative concentration pathway scenarios). Using similar approaches together with the quantified uncertainty ranges provided in this study could reveal the relative impact of large SOC estimate uncertainties on ESMs projections of the permafrost-climate feedback.

5 Conclusions

This study summarises present knowledge regarding estimated size and variability of SOC stocks in 0 to 3 m soils, deltas and the Yedoma region across the northern circumpolar permafrost region. The updated estimates of permafrost region SOC stocks are 217 ± 12 Pg for 0 to 0.3 m depth and 472 ± 27 Pg for 0 to 1 m depth (±95% CI). Estimated SOC storage between 0 and 3 m depth is 1034 ± 150 Pg, with SOC stocks roughly equally divided between physiographic regions of thick and thin sedimentary overburden. Of this, non-permafrost mineral soils store 158 Pg while poorly developed soils in the High Arctic store 34 ± 16 Pg. Estimated SOC storage below 3 m depth in deltaic alluvium of major Arctic rivers is 91 ± 52 Pg. In permafrost sediments of the Yedoma region, estimated SOC stocks below 3 m depth are 181 ± 54 Pg. Combined estimated SOC stocks in 0 to 3 m soils, deltaic deposits and

Yedoma region permafrost deposits for the entire northern circumpolar permafrost region are 1307 Pg with an uncertainty range of 1140 to 1476 Pg. An estimated 999 Pg of SOC is stored in permafrost terrain, of which 822 Pg is perennially frozen.

There are substantial regional gaps in pedon data to assess SOC storage below 1 m depth. Especially cryoturbated and organic (peatland) soils are highly variable and difficult to assess. The High Arctic bioclimatic zone and physiographic regions characterised by thin sedimentary overburden (areas of mountains, highlands, and plateaus) are poorly represented in the current pedon databases. Future field sampling to reduce these limitations should focus on the following observing strategies: (1) sampling soils in the full 0 to 3m depth interval throughout the permafrost region, (2) sampling soils in regions of thin sedimentary overburden and the High Arctic, and (3) sampling soils away from current data clusters, particularly in Eurasia. The estimates of SOC stocks in deltaic alluvium and Yedoma region deposits are also based on very limited observational evidence. Improved estimates of deposit thicknesses, mean SOC content and massive ice content could greatly reduce uncertainties in these estimates.

It is important to note that the presented uncertainty ranges do not account for errors in upscaling maps or analytical uncertainties in laboratory measurements. To quantify uncertainties arising from errors in upscaling maps, ground-truthing datasets for soil classification maps, deltaic alluvium extent and Yedoma region extent are needed. We also stress that substantial pools of SOC not included in this present study are stored below 3 m depth in soils and in unconsolidated sediments outside of the Yedoma region and deltaic deposits. The size and potential thaw-vulnerability of these additional SOC pools remains to be determined.

We conclude that soils and sediments of the northern circumpolar permafrost region store large amounts of SOC (~1300 Pg) but that this revised estimates shows that the fraction of SOC that is perennially frozen (~800 Pg) is substantially smaller than previously estimated.

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Figures

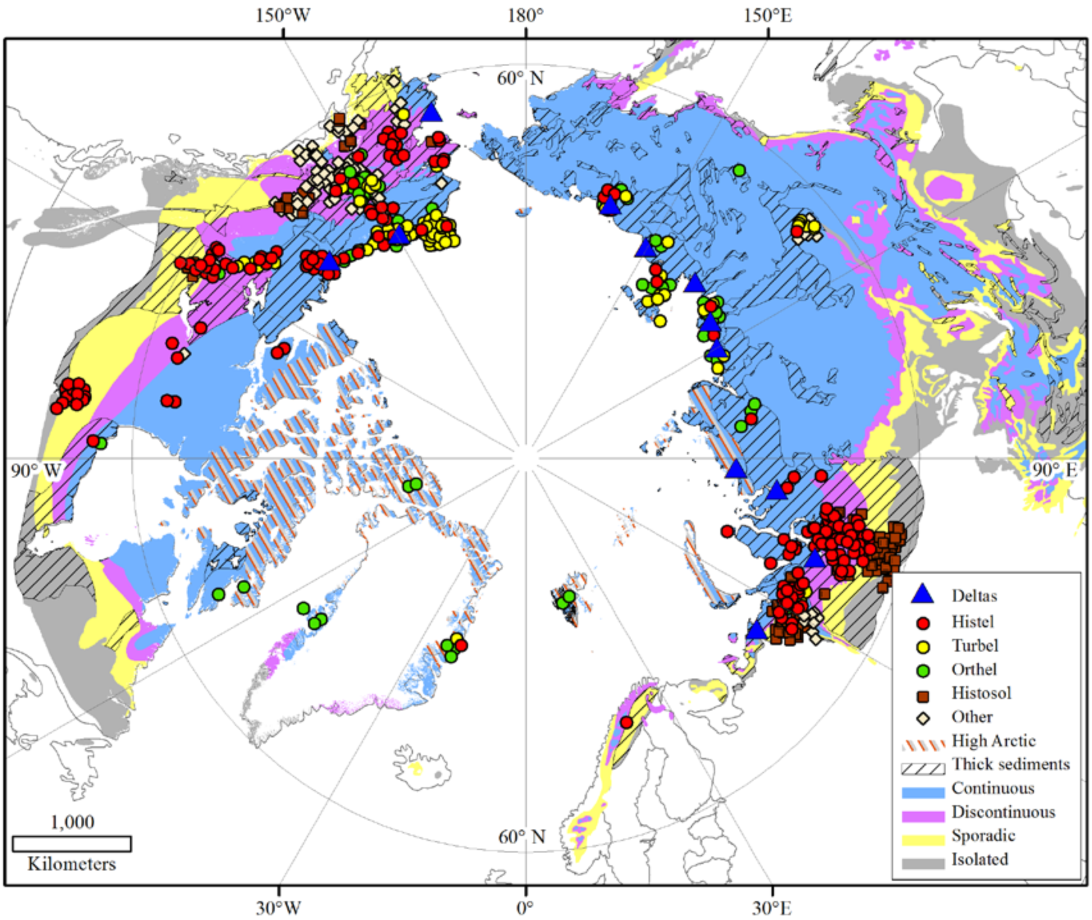

Figure 1. Geographical distribution of regions with thick sedimentary overburden and permafrost zonation in the northern circumpolar permafrost region (Brown et al., 2002). Map shows locations of the included Arctic river deltas as well as pedons with data in the 0 to 3 m depth range (pedon dataset 2), grouped according to NCSCDv2 upscaling classes. Exact pedon locations have been manipulated for cartographic representation; projection: Azimuthal Equidistant, datum: WGS84. Adapted from Hugelius et al. (2013a).

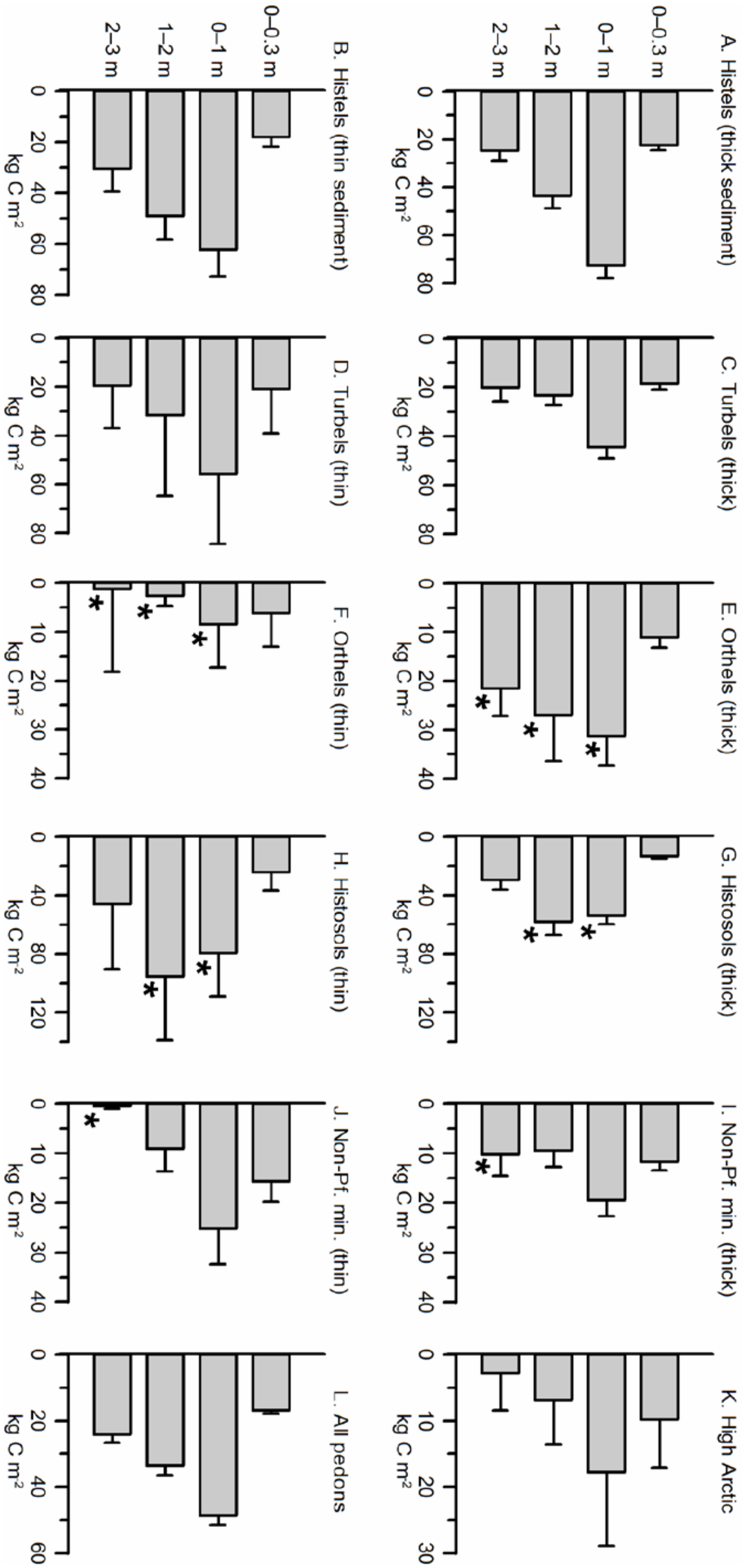
A. Histels (thick sediment)
B. Histels (thin sediment)
C. Turbels (thick)
D. Turbels (thin)
E. Orthels (thick)
F. Orthels (thin)
G. Histosols (thick)
H. Histosols (thin)
I. Non-Pf. min. (thick)
J. Non-Pf. min. (thin)
K. High Arctic
L. All pedons
0–0.3 m
0–1 m
1–2 m
2–3 m
kg C m-2

Figure 2. Mean SOC storage (kg C m^{-2}) with error bars showing 95% confidence intervals of the mean, for different soil upscaling classes calculated using pedon dataset 2. Different panels A to J show SOC storage estimates for the different depth ranges in areas of thick and thin sedimentary overburden, respectively. Panels K and J show mean SOC storage for the High Arctic region and for all pedons grouped together. Asterisks mark depth intervals in soil upscaling classes where SOC storage is significantly different from the equivalent interval in the other region (t-test, $p<0.05$).

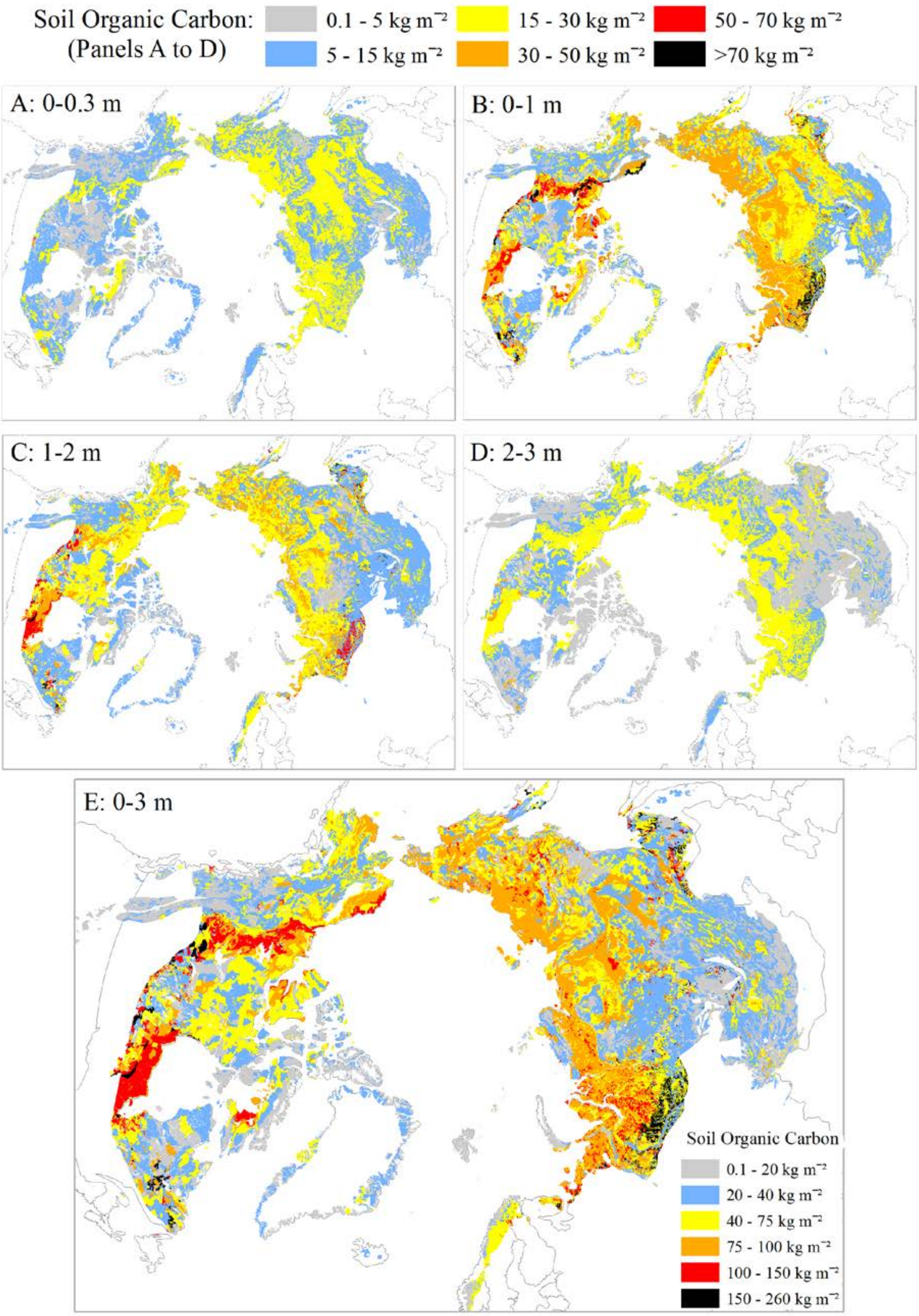
Soil Organic Carbon:
(Panels A to D)
0.1 - 5 kg m⁻²
5 - 15 kg m⁻²
15 - 30 kg m⁻²
30 - 50 kg m⁻²
50 - 70 kg m⁻²
>70 kg m⁻²
A: 0-0.3 m
B: 0-1 m
C: 1-2 m
D: 2-3 m
E: 0-3 m
Soil Organic Carbon
0.1 - 20 kg m⁻²
20 - 40 kg m⁻²
40 - 75 kg m⁻²
75 - 100 kg m⁻²
100 - 150 kg m⁻²
150 - 260 kg m⁻²

Figure 3. Map of estimated 0 to 3 m SOC storage (kg C m^{-2}) in the northern circumpolar permafrost region. Shows estimates based on sediment thickness upscaling. Panels show 0 to 1 m SOC calculated subdivided following NCSCD regions while 1 to 2 m and 2 to 3 m SOC is calculated subdivided for Eurasia vs North America and areas of thick vs thin sediments, respectively. Projection: Azimuthal Equidistant, datum: WGS84.

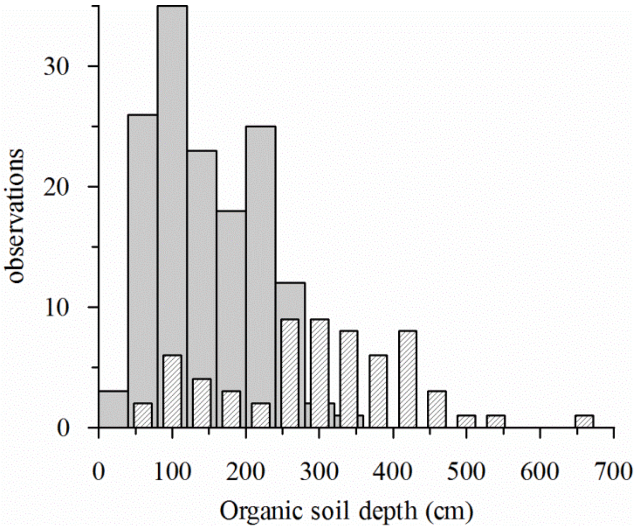

Figure 4. Histograms illustrating the depth-distribution of peat deposits (organic soil material) in Histosols and Histels of pedon dataset 2 (bins= 40 cm depth). The graph shows separate histograms for pedons that were gap-filled and/or extrapolated (wide gray bars) and pedons where no gap-filling and/or extrapolation were needed (narrow striped bars).

Table 1. Summary of number of available pedons (with > 1 m data) in areas with thick and thin sedimentary overburden for soil taxa from different regions (regional subdivision following NCSCD database structure) in the northern circumpolar region.

	Soil types (n of pedons at 1 to 2 m / 2 to 3 m depths)							
Soil order		*Gelisols*		*Histosols*	*Alfisols*	*Entisols*	*Inceptisols*	*Spodosols*
Soil suborder	*Histels*	*Turbels*	*Orthels*					
				Thick sediment				
NCSCD region[1]								
Alaska	27/27	52/8	27/8	1/1	-	8/1	37/8	2/-
Canada	30/29	4/3	5/3	6/6	2/2	3/1	9/5	-
Greenland	-	-	-	-	-	-	-	-
Scandinavia/Svalbard	1/1	-	2/2	-	-	-	-	-
Russia	89/89	22/14	27/21	60/60	-	1/1	2/-	4/1
Thick sed. sum:	147/146	78/25	61/34	67/67	2/2	12/3	48/13	6/1
				Thin sediment				
NCSCD region[1]								
Alaska	4/4	1/-	2/-	5/5	-	8/-	8/-	6/-
Canada	26/26	3/2	1/-	2/2	3/3	-	1/-	-
Greenland	-	-	3/-	-	-	-	-	-
Scandinavia/Svalbard	-	-	-	-	-	-	-	-
Russia	5/4	2/-	-	1/1	-	1/1	7/7	-
High Arctic[2]	1/1	1/1	6/2					
Thin sed. sum:	36/35	7/3	12/3	8/8	3/3	9/1	16/7	6/-
Total sum:	183/181	85/28	73/37	75/75	5/5	21/4	64/20	12/1

[1]There are no pedons in the NCSCD regions: Contiguous U.S.A., Mongolia, Iceland or Kazakhstan. [2]A total of eight Gelisol pedons from thin sediment regions were used separately to upscale soils of High Arctic tundra soils (five from Greenland and three from Canada).

Table 2. Summary of mean SOC storage in different depth ranges of the soil upscaling classes for the upscaling regions applied in this study. Numbers for soils above 1 m depth are based on pedon dataset 1 while numbers for soils from 1 to 3 m depth are based on pedon dataset 2. Note that for soils below 1 m depth all non-permafrost mineral soils (Non-pf. min.) are combined in one upscaling class. Per our definition of High Arctic soils, these soils are not found in physiographic regions with thick sedimentary overburden.

Region:	Circumpolar		Thick sediment		Thin sediment	
Depth range:	0 to 0.3 m	0 to 1 m	1 to 2 m	2 to 3 m	1 to 2 m	2 to 3 m
Soil class:	*SOC storage ± 95% CI (kg C m^{-2})*					
Alfisols	4.7 ± 0.4	7.9 ± 0.7				
Entisols	1.1 ± 0.8	7.7 ± 1.7				
Inceptisols	4.9 ± 0.2	9.5 ± 0.4				
Spodosols	11.7 ± 2	21.3 ± 5				
Natric soils	2.9 ± 0.6	10.6 ± 2.2				
Aquic soils	9.2 ± 0.4	16.8 ± 0.7				
Vertisols	5.7 ± 2.1	13.5 ± 4.9				
Mollisols	6.4 ± 0.4	12.2 ± 0.7				
Aridisols	1.6 ± 1.8	1.7 ± 5.4				
Andisols	11.4 ± 0.4	25.4 ± 0.2				
Ultisols	5.1 ± 1.2	9.4 ± 3.2				
Non-pf. min.			9.5 ± 3.3	10.3 ± 3.3	9.1 ± 4.6	0.5 ± 0.6
Histosols	22.5 ± 0.5	69.1 ± 0.9	58 ± 9	29.8 ± 9	95.7 ± 43.4	46.1 ± 44.2
Turbels	14.7 ± 1.5	33 ± 3.5	23.2 ± 4.1	20.1 ± 4.1	31.6 ± 33.1	19.5 ± 17.5
Orthels	15.8 ± 2.6	25.3 ± 4.1	27 ± 9.5	21.6 ± 9.5	2.6 ± 2	1.3 ± 16.9
Histels	18.1 ± 3	49.3 ± 8.4	43.6 ± 5.1	24.8 ± 5.1	49 ± 9.2	30.5 ± 8.8
High Arctic	9.8 ± 7.4	17.8 ± 11			6.9 ± 6.7	2.8 ± 5.6

Table 3. Summary of estimated soil area and SOC stocks (with ±95% CI where available) subdivided into physiographic regions of thick and thin sedimentary overburden (following Brown et al., 2002), the High Arctic region and summarized for the northern circumpolar permafrost.

	Thick sediments	Thin sediments	High Arctic region	Circumpolar
Soil area (km^2):	6.2×10^6 (35%)	10.6×10^6 (59%)	1.0×10^6 (6%)	17.8×10^6
SOC stocks (Pg):				
0 to 0.3 m	90	117	10 ± 3	217 ± 12
0 to 1 m	213	235	24 ± 8	472 ± 27
1 to 2 m	161 ± 14	187 ± 79	7 ± 5	355 ± 81
2 to 3 m	119 ± 16	86 ± 39	3 ± 3	207 ± 42
0 to 2 m	374	422	31 ± 13	827 ± 108
0 to 3 m	493	507	34 ± 16	1034 ± 150

Table 4. Summary of areal coverage (% of total permafrost region coverage) and total estimated SOC stocks (with % of total) of soil upscaling classes with reduced thematic resolution.

Soil classes	Area km^2	SOC stocks in 0 to 3 m Pg
Turbels [1]	5.5 (31%)	454 (44%)
Orthels [1]	2.3 (13%)	92 (9%)
Histels [1]	1.2 (7%)	147 (14%)
High Arctic soils [2]	1.1 (6%)	34 (3%)
High Arctic Turbels	0.7 (4%)	22 (2%)
High Arctic Orthels	0.2 (1%)	6 (0.6%)
High Arctic Histels	0.2 (1%)	6 (0.6%)
Gelisols sum: [3]	10.1 (57%)	727 (70%)
Histosols	0.9 (5%)	149 (14%)
Non-Gelisols, mineral	6.8 (38%)	158 (15%)
Total	17.8 × 10^6 km^2	1035 Pg

[1.] Applies to Gelisol suborders outside of the High Arctic region. [2.] A very small fraction (<1%) of the High Arctic is mapped as non-Gelisols but these soils are equally subdivided to Gelisol suborders here. [3.] Note that this class is not used in upscaling and is included here for summative purposes only.

Table 6 (Please note that this table should come after table 5 below, I simply put it here to avoid formatting problems in MS Word). Summative comparison of permafrost SOC stocks between the previous estimates in Tarnocai et al. (2009) and this study.

Soil organic carbon stocks	Tarnocai et al. (2009) Pg (% of region total)	This study Pg (% of region total)	Difference Pg
	Soils in the 0 to 3 m depth range		
Turbels	581 (35%)	476 (36%)	-105
Orthels	53 (3%)	98 (7%)	+45
Histels	184 (11%)	153 (12%)	-31
Sub-total Gelisols	818 (49%)	727 (56%)	-91
Gelisols in permafrost[1]	692 (41%)	572 (44%)	-120
Histosols	94 (6%)	149 (11%)	+55
Non-Gelisols, mineral	112 (7%)	158 (12%)	+46
Total for 0 to 3 m soils	1024 (61%)	1035 (79%)	+11
	Deposits below 3 m depth		
Deltaic alluvium	241 (14%)	91 (7%)	-150
Yedoma region	407 (24%)	181 (14%)	-226
	Combined SOC in soils (0 to 3 m), deltaic alluvium and Yedoma region sediments		
In permafrost terrain[2]	1466 (88%)	977 (75%)	-489
In permafrost[1]	1134 (68%)	822 (63%)	-312
Total permafrost region	1672	1307	-365

[1.] Estimated assuming an active layer depth of 30 cm or more in all Gelisols/High Arctic soils, following the methodology of Kuhry et al. (2013). [2.] Defined as storage in Gelisols/High Arctic soils and in permafrost in Yedoma or permafrost deltaic deposits below 3 m depth.

Table 5. Summary of input data and estimated total volume of alluvium and SOC stocks in major, permafrost-affected Arctic river deltas. In the cases where a parameter is taken from a map that reports ranges of data, the values used for calculations are given in brackets. For the estimated volume of alluvium, the fraction of alluvium that is perennially frozen is given in brackets.

River name	Delta area [a] (km^2)	Depth of alluvium (m)	Water bodies coverage (%)	Permafrost extent[h] (% value used for calculations)	Ground-ice content (%)[h] (% value used for calculations)	Alluvium SOC density mean± SD, kg C m^{-3} (n, sampling depth range)	Volume of alluvium, km^3 (% in permafrost)	Alluvium SOC stock, Pg (±95% CI)
Lena	32,000							
Active floodplain	13,203[g]	60	31[k]	Continuous (90)	>20 (25)	11.6±7.6 (n=7, 50–100 cm)[k]	651 (92)	8
First terrace	7,117[g]	60	31[k]	Continuous (90)	>20 (25)	29.9±15.1 (n=22, 50–100 cm)[k]	351 (92)	10
Second terrace	9,120[g]	60[b]	31[k]	Continuous (90)	>20 (25)	8.3±6.9 (n=3, 0–409 cm)[j]	450 (92)	4
Third terrace	2,560[g]	40[f]	NA[o]	Continuous (90)	>20 (25)	8.3±6.9[n]	97 (90)	0.8
Mackenzie	13,000	48[d]	41[i]	35–65%[c] (50)	5–15 (10)[c]	56.2±8.4[e] (n=5, 2–200 cm)	609 (51)	34
Yana	6,600	54[l]	36[l]	Continuous (90)	>20 (25)	25.8±18.8[l]	285 (91)	7
Indigirka	5,000	54[l]	36[l]	Continuous (90)	>20 (25)	25.8±18.8[l]	216 (91)	5
Yenisey	4,500	54[l]	36[l]	Continuous (90)	10–20 (15)	25.8±18.8[l]	201 (91)	5
Kolyma	3,200	54[l]	36[l]	Continuous (90)	>20 (25)	25.8±18.8[l]	138 (91)	4
Ob	3,200	54[l]	36[l]	Continuous (90)	10–20 (15)	25.8±18.8[l]	143 (91)	4
Pechora	3,200	54[l]	36[l]	Continuous (90)	<10 (5)	25.8±18.8[l]	148 (90)	4
Yukon	3,000	54[l]	36[l]	Continuous (90)	10–20 (15)	25.8±18.8[l]	134 (91)	3
Pyasina	1,000	54[l]	36[l]	Continuous (90)	>20 (25)	25.8±18.8[l]	43 (91)	1
Colville	600	54[l l]	36[l]	Continuous (90)	<10 (5)	21.2±3.8 (n=4, 55–270 cm)[m]	28 (90)	0.6
Olenek	500	54[l]	36[l]	Continuous (90)	>20 (25)	25.8±18.8[l]	22 (91)	0.5
Sum / mean	75,800 km^2	54 m	34%	83%	19%	26.0 kg C m^{-3}	3,514 (84%)	91 ±52 Pg

[a.] If nothing else is stated, delta areas are from Walker (1998). Refers to sub-aerial delta area. Note that subsea deltaic deposits or deltaic deposits covered under other deposits are not included in the current estimate.

[b.] Schwamborn et al. (2000), *in* Schwamborn et al. (2002)

[c.] Heginbottom (2000)

[d.] Mean calculated between the depth range 10-30 m (Aylsworth et al., 2000), ≥56 m (Smith et al., 2005), 50 m (Tarnocai et al., 2009), 55 m (Johnston and Brown, 1965) and 58 m (Taylor et al., 1996).

[e.] Tarnocai et al., (2009)

[f.] Assumed to be 60 m (Schwamborn et al., 2002) minus a 20 m Ice Complex coverage (Schirrmeister et al., 2011b)

[g.] Calculated based on proportional cover of geomorphic units reported by Zubrzycki et al. (2013) and references therein, assuming uniform water surface area distribution across the delta.

[h.] If nothing else is stated, permafrost extent and ground ice contents are from Brown et al., (2002). Ground ice content refers to segregation ice, injection ice and reticulate ice. Values are assumed to be valid for the upper 15 m of alluvium below which there is assumed to be no massive ice.

[i.] Smith (2011)

[j.] Schirrmeister et al., (2011b)

[k.] Zubrzycki et al. (2013)

[l.] Calculated mean from those delta regions where data is available.

[m.] Calculated based on data from Ping et al. (2011)

[n.] The fluvial sands underlying the third terrace Ice Complex deposit is assumed to have similar characteristics to the fluvial deposits in the second terrace (Schirrmeister et al., 2011b)

[o.] Not applicable, surface is covered by Ice Complex and not included in calculations

[p.] ±95% CI range are the combined uncertainties from estimates of mean alluvium SOC content (±18 Pg) and from estimates of mean alluvium depth (±49 Pg). Both estimates include representation error (see method section for details).