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Improved estimates show large circumpolar stocks of permafrost carbon while quantifying substantial uncertainty ranges and identifying remaining 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 stock estimates are poorly constrained and quantitative error estimates were lacking. This study presents revised estimates of the permafrost SOC pool, including quantitative uncertainty estimates, in the 0–3 m depth range in soils as well as for deeper sediments (> 3 m) in deltaic deposits of major rivers and in the Yedoma region of Siberia and Alaska. The revised estimates are based on significantly larger databases compared to previous studies. Compared to previous studies, the number of individual sites/pedons has increased by a factor × 8–11 for soils in the 1–3 m depth range„ a factor × 8 for deltaic alluvium and a factor × 5 for Yedoma region deposits. Upscaled based on regional soil maps, estimated permafrost region SOC stocks are 217 ± 15 and 472 ± 34 Pg for the 0–0.3 m and 0–1 m soil depths, respectively (±95 % confidence intervals). Depending on the regional subdivision used to upscale 1–3 m soils (following physiography or continents), estimated 0–3 m SOC storage is 1034 ± 183 Pg or 1104 ± 133 Pg. Of this, 34 ± 16 Pg C is stored in thin soils of the High Arctic. Based on generalised calculations, storage of SOC in deep deltaic alluvium (> 3 m to ≤ 60 m depth) of major Arctic rivers is estimated to 91 ± 39 Pg (of which 69 ± 34 Pg is in permafrost). In the Yedoma region, estimated > 3 m SOC stocks are 178 +140/−146 Pg, of which 74 +54/−57 Pg is stored in intact, frozen Yedoma (late Pleistocene ice- and organic-rich silty sediments) with the remainder in refrozen thermokarst deposits (±16/84th percentiles of bootstrapped estimates). A total estimated mean storage for the permafrost region of ca. 1300–1370 Pg with an uncertainty range of 930–1690 Pg encompasses the combined revised estimates. Of this, ≤ 819–836 Pg is perennially frozen. While some components of the revised SOC stocks are similar in magnitude to those previously reported for this region, there are also substantial differences in individual components. There is evidence of 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 > 3 m depth deposits in deltas and the Yedoma region.

1 Introduction

As permafrost warming and thaw occurs, large pools of SOC that were previously protected from decomposition 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 has demonstrated that permafrost C and associated climate feedbacks have been underestimated in previous modeling 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; MacDougal 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 SOM 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, 2011; Tarnocai and Stolbovoy, 2006; Schirrmeister et al., 2011a, b; 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 0–0.3 and 0–1 m SOC pools in the northern circumpolar permafrost region to be 191 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 0–3 m soil depth of 1024 Pg. This 0–3 m estimate was based on 46 Canadian pedons and was

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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 1–3 m SOC pools.

A first-order estimate of SOC storage in Yedoma terrain of 450 Pg (Zimov et al., 2006) was calculated from a small-scale map of Yedoma extent (Romanovskii, 1993), using generalized data of Yedoma deposit thickness, massive ice content, organic C% and bulk density. This estimate was revised 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 the Yedoma SOC pool may be 25 % to 50 % lower than previously reported because of overestimated Yedoma mean bulk density. 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 the SOC stored in permafrost sediments of the Yedoma region of Siberia and Alaska of 211 +160/−153 Pg (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 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., 2000).

Tarnocai et al. (2009) provided a total estimate of circumpolar SOC storage in soils (to 3 m depth), Yedoma and deltaic deposits of 1672 Pg, of which 1466 Pg is stored in perennially frozen ground. This is about twice as much C as what is currently stored in the atmosphere (Houghton, 2007). While it is recognized that this pool of SOC stored in permafrost regions is large and potentially vulnerable to rapid 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 (1–3 m), Yedoma and deltaic deposits were assigned the lowest degree of confidence (low to very low).

In this paper, we update and synthesize the current state of knowledge on permafrost SOC stocks at circumpolar scales. We revise of the permafrost SOC pool for the 0–3 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/pedons available for calculations has increased by a factor ×11 for 1–2 m soils, a factor ×8 for 2–3 m soils and deltaic alluvium and a factor ×5 for Yedoma region deposits. The first ever spatially distributed, quantified estimates for the 0–3 m depth range in soils are upscaled based on regional soil maps in the NCSCDv2. Primary 0–3 m SOC stock estimates are calculated by separating physiographic regions of thick and thin sedimentary overburden, corresponding to lowland and highland areas (Heginbottom et al., 1993; Brown et al., 2002). Following the subdivison used by Hugelius et al. (2013a) a secondary 0–3 m SOC stock estimate is also calculated separating the North American and Eurasian sectors. In recognition of limited soil development in some very 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

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to remove depth overlap with SOC stored in 1–3 m soils. The different components of the permafrost region SOC stocks are summarized and presented together with quantitative uncertainty estimates. A primary goal of this work is to quantify uncertainties associated with permafrost SOC pool estimates, and to improve SOC pool size and distribution for simulations of the permafrost-carbon feedback to the climate system.

2 Methods

More detailed descriptions of methods, including which datasets were used for different calculations, are available in the Supplement.

2.1 Calculating 0–3 m SOC stocks

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

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

The SOC stocks estimates for the 0–0.3 and 0–1 m depth ranges were calculated separately in each NCSCDv2-region (Alaska, Canada, Contiguous USA, Europe, Greenland, Iceland, Kazakhstan, Mongolia, Russia and Svalbard) following the methodology of Tarnocai et al. (2009).

Separate SOC stock estimates were calculated for areas with thin soils of the High Arctic region. Outside the High Arctic, we calculated two different estimates of 1–3 m SOC stocks based on separate geographical subdivisions. In the first estimate pedons and mapped soil areas in the northern circumpolar permafrost region were separated following physiographic regions of thick and thin sedimentary overburden (Fig. 1; following Heginbottom et al., 1993). Areas of thick sedimentary overburden corresponds to "areas of lowlands, highlands and intra- and inter-montane depressions characterized by thick overburden, wherein ground ice is expected to be generally fairly extensive" while areas of thin sedimentary overburden corresponds to "areas of mountains, highlands, and plateaus characterized by thin overburden and exposed bedrock, where generally lesser amounts of ground ice are expected to occur". This spatial subdivision was chosen because it is expected to reflect different important pedogenic proceses occurring across the studied region. For the second estimate, the northern circumpolar permafrost region was separated into the North American sector (includes Alaska, contiguous USA, Canada and Greenland) and the Eurasian sector (includes Europe, Iceland, Kazakhstan, Mongolia, Russia and Svalbard), respectively. This second estimate corresponds to the subdivision of Hugelius et al. (2013a).

The upscaled SOC stock estimates for the 0–0.3 and 0–1 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 sub-orders: Turbels (cryoturbated permafrost soils), Histels (organic permafrost soils) and Orthels (non-cryoturbated permafrost-affected mineral soils).

For the 1–2 and 2–3 m depth ranges, a reduced thematic resolution 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.

Near surface (0–0.3 and 0–1 m depth) SOC storage (kg C m^{-2}) values are based on 1778 individual pedons from around the northern circumpolar permafrost region (mainly Gelisol and Histosol pedons), that have been complemented with SOC storage (kg C m^{-2}) data from Batjes (1996) where data for non-permafrost soil orders was missing (this pedon dataset is hereafter called pedon dataset v1). More detailed information regarding this pedon dataset, including details regarding which soil orders were supplemented from Batjes (1996), can be found in Table S1 of the Supplement. For further details regarding the NCSCD GIS-database and the methods for pedon sampling and calculation of 0–0.3 and 0–1 m SOC stocks we refer to Hugelius et al. (2013b).

For the deeper soil layers (1–2 and 2–3 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 v2). Table 1 summarizes the number of individual pedons available from different geographical regions and areas of thick/thin sedimentary overburden. More detailed information regarding this pedon dataset can be found in Table S1 of the Supplement.

2.2 Calculating deltaic SOC stocks

The approach used to estimate deltaic SOC stocks in this study 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 storage (kg C m^{-3}) from the Mackenzie River Delta (Canada) combined with data on the spatial coverage of seven large arctic deltas. For the calculation presented here we combine 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 is calculated from the mapped sub-aerial delta extent and the mean depth of alluvial deposits,

subtracting the volume that is estimated to be occupied by massive ice and water bodies. To avoid double counting, the top 3 m of soil as well as known Yedoma deposits located in the Lena Delta are removed from the calculation. When the total volume of alluvium is calculated, the total SOC pool of each delta is estimated using field data of mean alluvium SOC storage (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 summarizes all input data (including references) used to estimate deltaic alluvium volume and SOC stocks. More detailed descriptions of calculations are available in the Supplement.

2.3 Calculating Yedoma region permafrost SOC stocks

For the purpose of these calculations, the permafrost deposits of the Yedoma region is subdivided into areas of intact Yedoma deposits (late Pleistocene ice- and organic-rich silty sediments) and permafrost deposits formed in thaw-lake basins (generalized as thermokarst deposits). Areas 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 permafrost thermokarst deposits for depths > 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). For details regarding calculations of the spatial extent of different sediments, data collection and spatial distribution of field observations we refer to 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 (10 000 times) observed independent values of the different parameters (following methodology of Strauss et al., 2013). After bootstrapping the populations of observations, the total mean pool size estimate was derived from these 10 000 bootstrap samples afterward. Because organic C% and bulk density of individual sediment samples are auto-correlated, paired values were used in the resampling process.

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 (i) database errors which are uncertainties caused by insufficient field-data representation to describe natural soil variability within an upscaling class and (ii) spatial errors which are uncertainties caused by areal misrepresentation of classes in the upscaling map (Hugelius, 2012). The former is quantified in this study and 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; however, this procedure assumes that the available sample accurately reflects the natural variability within a class. The latter 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 present 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 0–3 m soil SOC stocks and deltaic alluvium follow the procedures described by Hugelius (2012). These are 95 or 99 % confidence interval (CI) ranges calculated from the variance and proportional areal/volumetric contribution of each upscaling class.

The uncertainty ranges for Yedoma region deposits are the 16th and 84th percentiles of bootstrapped observations (following Strauss et al., 2013).

The uncertainty ranges of the different SOC stocks components are combined in two different ways: ($_{add}$CI) by addition of the relative CI ranges of different components or

($_{cov}$CI) by using a formula for additive error propagation of covarying variables (Roddick, 1987).

More detailed descriptions of all calculations, including fomulas, are available in the Supplement.

3 Results

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

The overall patterns of SOC content (kg C m^{-2}) are similar whether pedons are subdivided into physiographic regions of thick/thin sedimentary overburden (Fig. 2) or following continents into the North American/Eurasian sectors (Fig. 3) The highest mean SOC storage (kg C m^{-2}) are in the organic soils (Histosols and Histels; ca. 130–260 and 130–160 kg C m^{-2} in 0–3 m depth, respectively), followed by Turbels (ca. 60–110 kg C m^{-2}), Orthels (ca. 12–80 kg C m^{-2}) and non-permafrost mineral soils (ca. 30–40 kg C m^{-2}; Figs. 2 and 3). The eight available pedons in the High Arctic bioclimatic region have mean SOC contents of 9.8±8.5, 17.8±12.7, 6.9±.7.7 and 2.8±3.3 kg C m^{-2} in the 0–0.3, 0–1, 1–2 and 2–3 m depth ranges, respectively.

As pedon datsets v1 and v2 represent two independent statistical samples samples for estimating 0–1 m SOC storage (kg C m^{-2}) in the northern circumpolar permafrost region, inter-comparisons of these estimates are informative (Figs. 2 and 3, upper two bars of all panels). There are some notable differences between the datasets. There are no consistent trends between the two pedon datasets when separated following physiographic regions. But there are notable differences between pedon dataset v1 and v2 in Histels, Orthels and Histosols for thick-sediment regions (+36, −35 and −23 %, respectively), while for thin-sediment regions Turbels, Orthels and non-permafrost mineral soils stand out (+45 %, −69 % and +93 %, respectively; Fig. 2). In North America, all soil classes have higher SOC storage in pedon dataset v2 (30–100 % higher, largest difference for Turbels), while in Eurasia, Turbel and Histosol SOC storage is 25 and 35 % higher in pedon dataset v1 (Fig. 3). Comparing the 0–1 m SOC storage (kg C m^{-2}) values from the two pedon datasets when grouped for the whole northern circumpolar permafrost region revealed that there are no significant differences between the datasets for mean 0–1 m SOC storage (based on all circumpolar pedons) in the Orthel and Histel classes (t test, $p > 0.05$), while Turbels and non-permafrost mineral soils have significantly higher SOC and Histosols significantly lower SOC in pedon dataset v2 (t test, $p < 0.05$).

For consistency, in the following text only pedon dataset v2 is referred to regarding all descriptions or comparisons of SOC across regions or depth distribution of SOC within soil classes (Figs. 2 and 3, lower three bars of all panels). Looking at the mean SOC storage in the whole permafrost region, ca. 50 % of the 0–3 m SOC is stored in the upper 1 m of soil, but there are still significant amounts stored in the 1–2 m and 2–3 m depths (Fig. 3j). For Histosols, the highest estimated SOC storage is always in the 1–2 m depth range (Figs. 2 and 3).

Comparing areas 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 2–3 m depth (Fig. 2c, d, i, and j; t test, $p < 0.05$). At depths down to 2 m, Histosol SOC storage is significantly higher in thin sediment regions (Fig. 2g and h; t test, $p < 0.05$). The SOC storage estimates for North American Histosols and Turbels are significantly higher across all depth ranges than those for Eurasia (Fig. 3e–h; t test, $p < 0.05$). North American Histels store more SOC than Eurasian Histels > 1 m depth (Fig. 3a and b; t test, $p < 0.05$). Other soil upscaling classes show no significant differences between continents. More detailed information regarding the mean SOC storage (kg C m^{-2}) of different soil upscaling classes in all depth ranges can be found in Table S1 of the Supplement.

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. Regions with thick sediments occupy 35 % and regions with thin sediments 65 % of the soil area (Table 2). North America accounts for 39 % and Eurasia 61 % of the soil area (Table 3). Total estimated northern circumpolar permafrost region SOC stocks (±95 % CI) are 217 ± 15 Pg for the 0–0.3 m depth and 472 ± 34 Pg for the 0–1 m depth (Tables 2 and 3).

When upscaling based on physiographic regions (thick/thin sediments) estimated SOC stocks are 355 ± 90 Pg for the 1–2 m depth and 207 ± 54 Pg for the 2–3 m depth (Table 2). The summarized SOC stocks for 0–2 m depth is 827 ± 128 Pg and for 0–3 m depth is 1034 ± 183 Pg (95 % $_{add}$CI). When upscaling based on continental subdivision (North America/Eurasia), estimated SOC stocks are 355 ± 49 Pg for the 1–2 m depth and 277 ± 50 Pg for the 2–3 m depth (Table 3). The summarized SOC stocks for 0–2 m depth is 827 ± 83 Pg and for 0–3 m depth 1104 ± 133 Pg (95 % $_{add}$CI).

These numbers all include SOC in the High Arctic region which occupies 6 % of the northern circumpolar permafrost region and stores an estimated 34 ± 16 Pg SOC in the 0–3 m depth range (3 % of total permafrost region 0–3 m SOC stocks). Most of this is in the upper part of the soil with 10 ± 3 and 24 ± 8 Pg SOC in the 0–0.3 and 0–1 m depth ranges, respectively (95 % CI). Estimates for deeper soil layers in the High Arctic are lower, 7 ± 5 and 3 ± 3 Pg SOC in the 1–2 m and 2–3 m depth ranges, respectively.

Thick sediment areas have lower total SOC stocks than thin sediment areas in the 0–0.3 m, 0–1 m and 1–2 m depth ranges (corresponding to a significantly smaller areal coverage). However, in the 2–3 m depth range the total SOC stocks are higher in areas of thick sediments, reflecting the very low estimated SOC contents below 3 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 Table S1 of the Supplement). Maps of estimated SOC content (Fig. 4) show very clear differences in estimated SOC stocks, with higher numbers in thick sediment regions than in the thin sediment regions.

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There is a clear trend of wider CI-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 (Table 1).

In the upper 0–1 m of soil, there is considerably more SOC in Eurasian than North American permafrost regions (64 % and 36 % of total permafrost region 0–1 m SOC stocks, respectively), but for deeper depth ranges the SOC is almost equally divided between regions (Table 2). This corresponds to a clear pattern of higher estimated mean SOC storage ($kg C m^{-2}$) in North America compared to Eurasia for most upscaling classes in the 1–2 and 2–3 m depth ranges (Fig. 3), which is also evident from maps showing the spatial distribution of SOC storage across the permafrost region (Fig. S1 of the Supplement shows maps equivalent to Fig. 4, but with SOC upscaled following the continental subdivision).

Permafrost soils dominate SOC storage in the permafrost region, with 70 and 67 % of total stocks when upscaling following physiographic regions and continents, respectively (Table 4). Turbels outside of the High Arctic region, which account for 31 % of the soil area, store 38–46 % of total stocks (Table 4), and is the single dominant upscaling class across all depth ranges and regions (Table S1 of the Supplement). In the 1–2 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 (Figs. 2 and 3). Histosols are especially important in North America and areas of thick sediments, where the mean depth of peat deposits (data not shown) and mean SOC stocks are greater. Non-permafrost mineral soils cover 38 % of the northern circumpolar permafrost region, but accounts for ≤ 17 % of the SOC mass. More detailed information regarding the total soil area, SOC stocks and relative contribution of variance to the estimated ±CI ranges of different soil upscaling classes in all depth ranges can be found in Table S1 of the Supplement.

Estimates for permafrost soils are the most uncertain. For the 0–1 m SOC stock estimate, Turbels, Orthels and Histels together account for 89 % of the total estimated variance (61, 14 and 15 % respectively). At greater depths, uncertainties increase further.

Overall, the Turbels introduces the most variance to the SOC stock estimates across depth ranges, especially at > 1 m depths. Based on continent upscaling Turbels account for 32–67 and 43–48 % of variance (1–2 and 2–3 m depth ranges, respectively). For physiographic region upscaling, Turbels account for 54–89 and 72–90 % of variance (1–2 and 2–3 m depth ranges, respectively). The particularly large uncertainties of Turbel SOC content estimates in physiographic regions of thin sedimentary overburden are caused by few available pedons which show large within-class variability. The Histosols introduce considerable variance in the 1–2 and 2–3 m depth estimates in North America (37 and 36 % of North American SOC stock variance, respectively), while estimates are less varying in Eurasia and in areas of thick and thin sedimentary overburden (0.4–13 % of total variance, Table S1 of the Supplement). The Orthels show considerable variance in Eurasia (16 and 29 % for 1–2 and 2–3 m depths, respectively) and less in other upscaling regions 0.1–10 % of total variance). In the continent-based upscaling the variance from non-permafrost mineral soils increases in the 1–2 and 2–3 m depth ranges (15 and 19 % of total SOC stocks variance, respectively) compared to the estimated variance in the 0–0.3 and 0–1 m depth ranges (6 and 8 %, respectively). The relative uncertainties of High Arctic soil SOC stocks are large. However, these soils have low SOC stocks (0.2–4 % of total permafrost region SOC stocks across upscaling regions and depth ranges) and contribute little towards variance of the total estimates (0.03–7 % of total variance across upscaling regions and depth ranges).

3.3 Storage of SOC > 3 m depth in deltaic deposits

The total estimated area of major river deltas in the northern circumpolar permafrost region is 75 800 km^2 (Table 5). The estimate includes twelve deltas ranging in size from 500 to 32 000 km^2. The combined estimated alluvium volume > 3 m depth in these deltas is ca. 3 500 000 km^3 (stored between 3 and ≤ 60 m depth, mean alluvium depth is 54 m). Estimates for depth of alluvium 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 storage are available from the literature for five different delta units and range from 8.3 to 56.2 kg C m^{-3}. Estimated stocks of SOC in deltaic alluvium are 91 ± 39 Pg (95 % addCI). Because of high mean alluvium SOC storage (kg C m^{-3}) 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 51–92 % (mean 84 %) of deltaic alluvium is stored in permafrost. Estimated SOC stocks in perennially frozen alluvium are 69 ± 34 Pg (95 % $_{add}$CI).

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 (±28/37 Pg, 95/99 % CI) are greater than uncertainties from poorly estimated alluvium SOC storage (±11/15 Pg, 95/99 % CI).

3.4 Storage of permafrost SOC > 3 m depth 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) (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 (> 3 m depth) in the Yedoma region is 178 +140/−146 Pg (ranges are 16/86th percentiles of bootstrapped means). Of this an estimated 74 +54/−57 is stored in intact Yedoma while 105 +86/−89 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 significantly improved databases. The study includes the first spatially distributed quantification of 1–3 m SOC stocks as well as the first quantitative uncertainty ranges for SOC stocks in this region. Compared to previous studies (Tarnocai et al., 2009; Zimov et al., 2006), the number of individual field sites/pedons available for calculations in this study has increased by a factor ×11 for 1–2 m soils (from 46 to 518), a factor ×8 for 2–3 m soils (from 46 to 351), a factor ×8 for deltaic alluvium (from 5 to 41) and a factor ×5 for Yedoma region deposits (from 6 to 32). Despite this, analyses of estimate uncertainties and the spatial distribution of input data show that substantial regional data-gaps remain. In part, revised SOC stock estimates are similar to those previously reported, but for some components of the permafrost SOC stocks, there are substantial differences.

4.1 Updated circumpolar permafrost region SOC stocks

The updated estimates of northern circumpolar permafrost region SOC stocks in 0–0.3 m (217 ± 15 Pg) and 0–1 m (472 ± 34 Pg) are largely based on the same data as the equivalent estimates of Tarnocai et al. (2009) (191 and 495 Pg, respectively). 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, b) and to new SOC estimates for the High Arctic region. Compared to the previous estimate of 1024 Pg SOC in 0–3 m soils (Tarnocai et al., 2009), the new revised estimates differ by either +10 Pg (physiographic region upscaling: 1034 ± 183) or +80 Pg (continent upscaling: 1104 ± 133 Pg). The physiographic subdivision is better suited to reflect different soil types across the northern circumpolar permafrost region and this approach should arguably provide a more realistic assessment of 0–3 m SOC distribution (Fig. 4). The updated pedon database (v2) includes spatial representation across the northern circumpolar permafrost region and a ca. ten-fold increase in the number of pedons compared to that of Tarnocai et al. (2009). Despite this, the relative changes in the total 0–3 m SOC stocks compared to Tarnocai et al. (2009) fall well within the 95 % CI ranges. However, there are larger differences in SOC stock estimates between individual soil classes in the two studies (see Sect. 4.2.1 below).

The updated estimate of SOC stored in deltas of major rivers in the northern circumpolar permafrost region (91 ± 39 Pg) is considerably lower than the earlier equivalent estimate (241 Pg; Tarnocai et al., 2009). While the new estimate uses many sources of data that differ from the initial estimate (Table 5), the main cause for the significant reduction is that including new field data greatly reduced the estimated mean SOC content ($kg\,C\,m^{-3}$) in alluvial deposits.

The updated estimate of permafrost SOC storage > 3 m depth in the Yedoma region (178 +140/−146) is based on the same methodology and dataset as the estimate for the total permafrost SOC stocks in this region of 211 +160/−153 Pg, developed by Strauss et al. (2013). Removing depth overlap with the 0–3 m soil estimate resulted in a reduction of 33 Pg. The reduction from 407 Pg to 178 Pg compared to the previous depth-integrated estimate (Tarnocai et al., 2009) is mainly caused by a twofold reduction of estimated bulk density and different assumptions regarding the characteristics of intact Yedoma compared to refrozen thermokarst sediments (Fig. 3 in Strauss et al., 2013).

Because of the various upscaling uncertainties and regional data-gaps inherent in these estimates (see further discussion below), we consider it more realistic, and advisable, to use the wider $_{add}$CI ranges rather than the narrower $_{cov}$CI ranges (Tables 2 and 3). Adding up SOC stocks in 0–3 m soils, deltaic deposits and Yedoma region permafrost deposits for the northern circumpolar permafrost region results in estimates of 1303 +362/−368 Pg or 1373 +312/−318 Pg (with physiographic region and continent upscaling for soils, respectively; 95 % $_{add}$CI). Of this, 974–991 Pg of SOC is stored in permafrost terrain (defined as storage in Gelisols/High Arctic soils and in permafrost in Yedoma or permafrost deltaic deposits > 3 m depth). Storage of SOC in permafrost is estimated to be ≤ 819–836 Pg or 61–63 % of total permafrost region stocks (assuming

an active layer depth of ≥ 30 cm in all Gelisols/High Arctic soils). This is a considerable reduction compared to the previous estimate of 1466 Pg (or 88 %) of SOC in permafrost (Tarnocai et al., 2009).

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

4.2.1 SOC distribution by regions

Despite the wider uncertainty ranges in physiography-based upscaling, we argue that this approach reflects a more accurate assessment of SOC distribution than subdivision by continent. The estimate upscaled based on physiographic regions reflects differences between upland and lowland areas across the northern circumpolar permafrost region (Heginbottom et al., 1993). This alternative for upscaling is better suited to reflect the different soil types and important pedogenic processes that occur across the permafrost region. It is consistent with other studies which have utilized physiography and its influence on soil drainage to upscale soil properties (Harden et al., 2003; Yi et al., 2009). Maps of mean SOC storage (Figs. 4 and S1 of the Supplement) illustrate clear differences between the two upscaling methods. Based on continent upscaling, there is clearly more SOC estimated in the 1–2 and 2–3 m depth ranges in the North American region than in Eurasia (Figs. 3 and S1 of the Supplement). When upscaling is separated based on physiography, different patterns emerge. For example, in the 1–2 m depth range, mountainous regions in Siberia emerge as having low > 1 m SOC pools. Also, the estimated mean SOC storage in North American regions with large peatland expanses are lower and there are no areas with > 50 $kg\,C\,m^{-2}$ estimated at > 2 m depths. In thin sediment areas (“areas of mountains, highlands, and plateaus characterized by thin overburden and exposed bedrock, where generally lesser amounts of ground ice are expected to occur”, Heginbottom et al., 1993) we would generally expect conditions to be less favorable for accumulation of large SOC stocks than in areas of thick sediment overburden (“areas of lowlands, highlands and intra- and inter-montane depressions characterized by thick overburden, wherein ground ice is expected to be

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generally fairly extensive"). The overall upscaled SOC stock estimates follows this pattern of higher stocks in thick sediment areas, but some individual soils classes do not. However, our estimates for thin sediment areas are characterized by large variability, poor pedon representation, and wide uncertainty ranges (see Sect. 4.3.1 below).

In recognition of the limited soil development in high latitude areas with thin sediments, the High Arctic region was treated separately in upscaling. This region covers ca. 6 % of the northern circumpolar permafrost region and is estimated to store 34 ± 16 Pg SOC in the 0–3 m depth range (3 % of total 0–3 m SOC stocks). A previous study estimated active layer SOC stocks for this region to be 12 Pg (Horwath Burnham and Sletten, 2010), which falls within current estimates of 10 ± 3 and 24 ± 8 Pg SOC in the 0–0.3 m and 0–1 m depth ranges, respectively.

4.2.2 SOC distribution by soil types

In general, the permafrost soils and organic soils dominate 0–3 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). While our overall 0–3 m SOC stock estimates are very similar to those presented by Tarnocai et al. (2009), there are considerable differences between individual soil orders. The revised estimates are considerably lower for Turbels (−106 Pg or −22 %) and Histels (−31 Pg or −20 %) but higher for Orthels (+45 Pg or +85 %), Histosols (+55 Pg or +59 %) and non-permafrost mineral soils (+46 Pg or +41 %) (all differences from physiographic region upscaling calculated relative to numbers presented in Kuhry et al., 2013, Table 1).

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 38–46 % of 0–3 m SOC stocks with 36 % areal coverage, Table 4). There are notable differences in Turbel mean SOC storage (kg C m^{-2}) across regions.

The data in pedon dataset v2 indicates that Turbels in North America are more SOC-rich than in Eurasia (t test, $p < 0.05$), while in pedon dataset v1 this pattern is reversed (Fig. 3). When separating the permafrost region into physiographic regions there are no significant differences in mean Turbel SOC storage between regions, but there is notable variability in the data at all depths.

The mean SOC storage (kg C m^{-2}) is highest in organic soils (Histosols and Histels, Figs. 2 and 3), and these soils also contribute significantly towards total SOC stocks (14–16 and 13–14 % of 0–3 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 valley, are mapped as especially SOC-rich across depths (Fig. 4). There is relatively large variability in SOC storage of organic soils across regions. Histels and Histosols in North America have deeper peat deposits and higher SOC storage than those in Eurasia (Fig. 3). Unexpectedly, the upper 2 m of Histosols in areas of thin sediment overburden have significantly higher SOC density (kg C m^{-2}) 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 fully evaluate this.

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 stocks of SOC have accumulated over long time scales (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 areas of thin sediments (corresponding to upland or montane areas) store little SOC while Orthels in thick sediment areas have accumulated significant SOC stores down to 3 m depth (Fig. 3)

Especially in areas of discontinuous permafrost (commonly in regions of boreal forest), a large fraction of the landscape is non-permafrost mineral soil (38 % of total permfrost region soil area), which also store significant amounts of SOC (15–17 % of total 0–3 m SOC stocks). Irrespective of regional subdivision, these soils store ca.

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20 kg C m^{-2} in the upper meter (pedon dataset v2), but C storage at greater depths is typically considerably lower (≤ 10 kg C m^{-2}; Figs. 2 and 3). Within O and A horizons, high SOC storage may indicate accumulation of humified organics, charcoal, or char-mediated sorption in fire-prone boreal forests. Beneath O and A soil horizons, important mechanisms for stabilizing SOC in these soils include deep rooting or sorption of leached dissolved OC to clay particles or formation of complexes with iron and/or aluminium. Low SOC storage in deeper horizons > 1 m 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 thin sediment regions 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 Estimate uncertainties and data gaps

This study presents the first quantitative uncertainty ranges for estimates of northern circumpolar permafrost region SOC stocks. The widest uncertainty ranges are associated with those 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 (1–3 m), Yedoma and deltaic deposits.

For 0–3 m soils and deltaic deposits CI-ranges are calculated based on within-class variability of pedons (or alluvial deposit thickness) and areal coverage of classes. For Yedoma region SOC stocks, the uncertainty ranges correspond to the 16/84th 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 approach allows non-normality but also differs in that it does not integrate individual sediment layers or horizons at the site/pedon level. The use of different approaches to quantify uncertainties in the various pools complicates comparisons, but it is clear that there is a wide overall uncertainty range on the order of ±30 % for the ca.

1300–1370 Pg total permafrost region SOC pool. 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 in e.g. the High Arctic, Central Siberia and many deltas.

4.3.1 Regional uncertainties of estimates for 0–3 m soils

The estimates of SOC stocks in 1–3 m soils are based on a highly generalized upscaling scheme, where 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 and North America/Eurasia, respectively). For the estimate of 0–1 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 (kg C m^{-2}) values were individually assigned to mapped soil-series (Alaska) or soil-names (Canada). Because of these methodological differences, there are some discrepancies across depths for estimates in Alaska and Canada, where 1–2 m or 2–3 m soil layers are sometimes estimated to hold more SOC than the upper meter of soils. This applies e.g. to some areas in the Western Hudson Bay Lowlands and parts of the Arctic Canadian archipelago outside of the High Arctic zone. Clear trends of decreased SOC storage with depth in all soil classes (except Histosols; Figs. 2 and 3), indicate that these vertical patterns in SOC storage are not realistic.

The estimated uncertainty ranges of SOC stocks rely 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). 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 variance and confidence intervals 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, there is relatively poor replication of Turbels in pedon database v2 for Eurasia and very poor representation for thin sediment regions outside of the High Arctic ($n = 6$ and 2 for the 1–2 and 2–3 m depths, respectively). The thin sediment region also has poor representation of Histosols and Orthels. The 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. 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.

4.3.2 Differences between soil pedon databases and sampling biases

For the 0–1 m depth interval, two independent sources of pedon data to estimate SOC storage (kg C m^{-2}) are available (pedon dataset v1 used to calculate 0–1 m SOC stocks and pedon dataset v2 used to calculate 1–3 m SOC stocks). While pedon dataset v2 was not actually used in the quantification of 0–1 m SOC stocks, estimates are available for that depth range. If we assume that the two independent datasets are accurate samples of 0–1 m SOC stocks, there should be no significant differences between the datasets. However, there are discrepancies between the databases which indicate that the sampling for > 1 m depth in soils may have been biased. There is no independent dataset against which we can verify estimates for 1–3 m soils. Because near surface pedon SOC storage is correlated to > 1 m depth SOC storage (see Sect. 1.4.3 of the extended method description in the Supplement) we infer that the significant

differences in 0–1 m SOC storage could be an indication of data-biases in the dataset. Summarized 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 v2. Because data for pedon datset v1 is only available aggregated to the whole permafrost region, no statistical comparisons can be made at regional levels. Relative comparisons reveal that in North America pedon dataset v2 is consistently estimating higher values than pedon dataset v1 (Fig. 2). In other regions, there are no clear patterns and results differ across soil classes (Figs. 2 and 3).

There is an indicated bias towards high SOC in Turbels of pedon dataset v2. Closer examination of regional patterns reveals that this is largely due to very high SOC storage estimates for North American Turbels (at all depths). For Eurasian Turbels the pattern is opposite with higher estimates in pedon dataset v1 and 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 v2 is geographically clustered (Fig. 1; Hugelius et al., 2013a) and more dispersed samples of pedons from across regions could reduce any biases introduced by this clustering.

Hugelius et al. (2013a) discuss a potential depth bias for organic soils where e.g. targeted sampling campaigns may cause sites with thick peat deposits to be overrepresented in datasets. To avoid such a bias, pedon dataset v2 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. 5). 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 (data not shown, calculated based on physiographic region upscaling). The estimated error introduced by applying default values is on the order of ±2 Pg (calculated from the standard error of mean of the applied default values and mean extrapolation depth of pedons). The use of sites where data on mineral subsoils was extrapolated may be one factor explaining the indicated low-bias of Histosols in pedon dataset v2 when compared to pedon dataset v1.

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 database v1. However, estimated SOC storage for most of these pedons are from the global scale ISRIC database (Batjes, 1996; Table S1 of the Supplement; applies to all Eurasian permafrost-free soils and North American Aridisols, Andisols and Ultisols in pedon dataset v1). Because of this, the data used for much of the non-permafrost mineral soils in pedon dataset v1 is likely not truly representative of soils in the permafrost region.

4.3.3 Data availability and uncertainties of estimates for deltaic deposits

The previous estimate of deltaic SOC stocks (241 Pg) by Tarnocai et al. (2009) was based on field data from the Mackenzie River Delta extrapolated to seven major deltas of the permafrost region. The revised, substantially smaller, estimate presented here (91 ± 39 Pg) builds on this same basic methodology, but with additional sources of data from the literature. The difference between estimates is mainly caused by lower estimates of mean alluvium SOC content (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 for the updated source is based on an entirely different source (Walker, 1998) and includes the twelve major deltas in the permafrost region, the difference in total estimated sub-aerial delta surfaces is relatively small. The estimated depth of alluvium in deltas is also similar to the first estimate. Tarnocai et al. (2009) do not consider any reduced alluvium volume caused by occurrences of massive ice. In this study, massive ice content in deltas was estimated based on the Brown et al. (2002) map. If no massive ice content is assumed, the estimate would increase to 98 ± 42 Pg.

The updated estimate of deltaic SOC storage confirms that a substantial pool of permafrost SOC is stored in these deposits, but it is also clear that more field observations are needed to refine estimates. The calculated CI ranges indicate that uncertainties are larger concerning alluvium depth than mean SOC storage, but the observational base for both estimates are very small and from most major deltas no field observations are available (Table 5). The current estimates rely on the assumption that alluvial SOC contents measured in the near surface can be extrapolated to full depth. Further, the calculated CI ranges assume a correct spatial extent of deltas and correct volumetric extent of water bodies and massive ice.

4.3.4 Uncertainties 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 thirty-two sites 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. The wide reported uncertainty ranges (±75 %) include the total data uncertainty. As stated in Sect. 1.4.2 of the extended method section (Supplement), a single estimator's uncertainty based on mean values from different bootstrapping runs would be remarkably lower, but would neglect the natural inherent heterogeneity of the measurements.

To improve Yedoma region SOC stock calculations, 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 km^2 for regions with smaller known Yedoma occurrences (e.g. south of Taymyr Peninsula and Chukotka in Russia and Yukon Territory in Canada). To describe the spatial fragmentation of intact Yedoma deposit remnants, we used a Yedoma coverage of 30 %, which is dissected by thermokarst (56 %). The rest of the Yedoma region (14 %) is excluded as described in Sect. 3.4. To improve this simplified approach, an uncertainty reduction could be reached by implementing spatially explicit data off 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 northwestern Canada are currently not available.

4.3.5 Spatial upscaling errors

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 estimate uncertainty ranges. A regional study of the Northern Usa River Basin (Russian Arctic) showed that uncertainties from map errors were similar in magnitude as errors from insufficient pedon representation or natural variability (both estimated at ±8 % for 0–1 m SOC stocks; Hugelius, 2012). Because no dedicated ground-truthing dataset is available to assess e.g. the NCSCD soil maps that form the spatial base of upscaling SOC in 0–3 m soils, we cannot directly quantify

this error. We recognize that 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 spatial errors in the maps used in this study to be equal to or greater than those found for the Northern Usa River Basin. 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.

4.4 Additional permafrost deposits with significant SOC stocks below 3 m depth

This current and the previous (Tarnocai et al., 2009) estimates of SOC stocks in the northern circumpolar permafrost region includes 0–3 m soils, 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 > 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 v2 in this study, 17 % have peat deposits extending > 3 m depth (Fig. 5) and these 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. 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 (e.g. Hugelius et al., 2011; Schirrmeister et al., 2011a; Ping et al., 2011 etc.). Following the physiographic subdivision, 6.2×10^6 km^2 of the permafrost region is characterized by thick sedimentary overburden (sediments > 5–10 m thick; 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 > 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 pools of permafrost SOC stored in 0–3 m soils, deltas and the Yedoma 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/thermoerosion can affect substantial fractions of permafrost landscapes over decadal timescales (Jones et al., 2011, 2013; Hugelius et al., 2011, 2012; Sannel and Kuhry, 2011).

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). Also, fire-driven reductions in organic-horizon thickness decrease sub-soil insulation cause active layer deepening, which can increase the amount of SOC 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; MacDougal 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. Furthermore, the complexity of ESMs 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 pools 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 summarizes present knowledge regarding estimated size and variability of SOC stocks in 0–3 m soils, deltas and the Yedoma region across the northern circumpolar permafrost region. Compared to previous studies, the number of individual sites/pedons has increased by a factor ×8–11 for 1–3 m soils, a factor ×8 for deltaic alluvium and a factor ×5 for Yedoma region deposits.

The updated estimates of permafrost region SOC stocks are 217 ± 15 Pg for 0–0.3 m depth and 473 ± 34 Pg for 0–1 m depth (±95 % CI). Estimates for 0–3 m SOC storage are 1034 ± 183 Pg, with > 1 m soils upscaled based on a subdivision following physiographic regions of thick/thin sedimentary overburden. A secondary estimate of 0–3 m SOC storage based on a separation of the North American/Eurasian regions is 1104 ± 133 Pg. Of this, 34 ± 16 Pg C is stored in poorly developed soils of the High

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Arctic. Estimated SOC storage > 3 m depth in deltaic alluvium of major tweleve major permafrost river deltas is 91 ± 39 Pg (of which 69 ± 34 Pg is in permafrost). The uncertainty ranges of revised estimates encompass the previous estimates for SOC stocks in 0–3 m soils, but not for deltaic deposits where the estimate is lowered considerably (Tarnocai et al., 2009). In permafrost sediments of the Yedoma region, estimated > 3 m SOC stocks are 178 +140/−146 Pg (of which 74 +54/−57 Pg is in intact Yedoma). Depending on whether soils are upscaled by subdividing physiographic regions or continents, added SOC stocks in 0–3 m soils, deltaic deposits and Yedoma region permafrost deposits for the entire northern circumpolar permafrost region are estimated at 1304 +362/−368 Pg or 1373 +312/−318 Pg, respectively (95 % addCI). We argue that the former estimate is better suited to reflect the different soil types and important pedogenic processes occuring across this region. An estimated mean storage of ca. 1300–1370 Pg with an uncertainty range of 930–1690 Pg encompasses both estimates. Of this 974–991 Pg of SOC is stored in permafrost terrain and ≤ 819–836 Pg (61–63 %) is perennially frozen.

The wide uncertainty range reflects difficulties in assessing highly variable SOC stocks across large geographic expanses based on limited field data. There are substantial regional gaps in pedon data to assess > 1 m SOC storage. Especially cryoturbated soils and organic soil orders are highly variable and difficult to assess. The High Arctic bioclimatic zone and physiographic regions characterized by thin sedimentary overburden (areas of mountains, highlands, and plateaus) are poorly represented in the current pedon databases. Thin sediment regions cover 65 % of the total area but holds only 17–19 % of available pedons in the > 1 m depth ranges. Only eight pedons are available for estimating > 1 m SOC stocks in the High Arctic bioclimatic zone (ca. 1×10^6 km^2). Uncertainty ranges for SOC in 1–3 m soils are > ±40 % in thin sediment regions and ±70–100 % in the High Arctic. Future field sampling to reduce these limitations should focus on the following observing strategies: (1) sampling soils in the full 0–3 m depth interval throughout the permafrost region, (2) sampling soils in thin overburden areas, 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 little observational evidence (*n* sites = 41 and 32, respectively) with uncertainty ranges of > ±40 and ±80 %, respectively. Improved observational data on deposit thicknesses, mean SOC content and massive ice content could greatly improve these estimates.

It is important to note that the presented uncertainty ranges do not account for errors in upscaling maps. Previous studies from permafrost terrain have demonstrated that such spatial upscaling errors can be similar to errors from natural pedon variability and/or insufficient pedon database replication. 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 are likely stored in > 3 m depth soils and unconsolidated sediments that are not included in this present study. The size and potential thaw-vulnerability of this additional SOC pool remains to be determined.

We conclude that soils and sediments of the northern circumpolar permafrost region store large amounts of SOC (1300–1370 Pg). But current efforts at quantifying these pools are associated with large estimate uncertainties (on the order of ±25–30 % for the whole region) and large regional data gaps remain.

Supplementary material related to this article is available online at http://www.biogeosciences-discuss.net/11/4771/2014/bgd-11-4771-2014-supplement.zip.

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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 structure).

	Soil types (*n* of pedons at 1–2 m/2–3 m)							
Soil order	Gelisols			Histosols	Alfisols	Entisols	Inceptisols	Spodosols
Soil sub-order	Histels	Turbels	Orthels					
				Thick sediment				
NCSCD region[a]								
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[a]								
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[b]	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

[a] There are no pedons in the NCSCD regions: Contiguous USA, Mongolia, Iceland or Kazakhstan.
[b] 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 estimated soil area and SOCM mass (with 95 % CI and 99 % CI) subdivide into physiographic regions of thick and thin sedimentary overburden (following Brown et al., 2002) and summarized for the northern circumpolar permafrost region (NA = not available).

		Thick sediments		Thin sediments		Circumpolar	
Soil area (km^2):		6.2×10^6 (35 %)		11.6×10^6 (65 %)		17.8×10^6	
SOC stocks (Pg):							
0–0.3 m	±95 % CI ±99 % CI	90	NA NA	127	NA NA	217	13 17
0–1 m	±95 % CI ±99 % CI	213	NA NA	259	NA NA	472	27 36
1–2 m	±95 % CI ±99 % CI	161	14 19	194	81 106	355	95 125
2–3 m	±95 % CI ±99 % CI	119	16 22	88	38 51	207	54 73
0–2 m	±95 % $_{add/cov}$CI ±99 % $_{add/cov}$CI	374	NA NA	453	NA NA	827	128/101 169/132
0–3 m	±95 % $_{add/cov}$CI ±99 % $_{add/cov}$CI	493	NA NA	541	NA NA	1034	183/116 241/151

Table 3. Summary of estimated soil area and SOCM mass (with 95 % CI and 99 % CI) subdivided into North America and Eurasia and summarized for the northern circumpolar permafrost region (NA = not available).

		North America		Eurasia		Circumpolar	
Soil area (km^2):		7.0×10^6 (39 %)		10.8×10^6 (61 %)		17.8×10^6	
SOC stocks (Pg):							
0–0.3 m	±95 % CI	72	NA	146	NA	217	15
	±99 % CI		NA		NA		20
0–1 m	±95 % CI	170	NA	302	NA	472	34
	±99 % CI		NA		NA		44
1–2 m	±95 % CI	170	21	185	28	355	49
	±99 % CI		28		37		65
2–3 m	±95 % CI	131	26	146	24	277	50
	±99 % CI		34		32		66
0–2 m	±95 % $_{add/cov}$CI	340	NA	487	NA	827	83/60
	±99 % $_{add/cov}$CI		NA		NA		109/79
0–3 m	±95 % $_{add/cov}$CI	471	NA	633	NA	1104	133/78
	±99 % $_{add/cov}$CI		NA		NA		176/103

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. Results are presented separately for upscaling based on separating North America and Eurasia (continent upscaling) and upscaling based on separating areas of thick and thin sedimentary overburden (sediment upscaling).

Soil classes	Area	Continent upscaling 0–3 m SOC stocks	Sediment upscaling 0–3 m SOC stocks
Turbels[a]	31 %	405 Pg (37 %)	453 Pg (41 %)
Orthels[a]	13 %	160 Pg (15 %)	92 Pg (8 %)
Histels[a]	7 %	144 Pg (13 %)	147 Pg (13 %)
High Arctic soils[b]	6 %	34 Pg (3 %)	34 Pg (3 %)
High Arctic Turbels	4 %	22 Pg (2 %)	22 Pg (2 %)
High Arctic Orthels	1 %	6 Pg (0.6 %)	6 Pg (0.6 %)
High Arctic Histels	1 %	6 Pg (0.5 %)	6 Pg (0.6 %)
Gelisols sum[c]:	58 %	744 Pg (67 %)	727 Pg (70 %)
Histosols	5 %	175 Pg (16 %)	149 Pg (14 %)
Non-permafrost mineral soils	38 %	184 Pg (17 %)	158 Pg (15 %)
Total	17.8×10^6 km^2	1104 Pg	1034 Pg

[a] Applies to Gelisol suborders outside of the High Arctic region.

[b] A very small fraction (< 1 %) of the High Arctic is mapped as non-Gelisols but these soils are equally subdivided to Gelisol suborders here.

[c] Note that this class is not used in upscaling and is included here for summative purposes only.

Table 5. Summary of input data and estimated total volume of alluvium and SOC stocks in major, permafrost affected Arctic deltas.

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 storage mean ± SD, $kg\,C\,m^{-3}$ (*n*, sampling depth range)	Volume of alluvium, $km^3 \times 10^3$ (% in permafrost)	Alluvium SOC stock, Pg
Lena	32 000							
Active floodplain	13 203[g]	60 m	31 %[k]	Continuous (90 %)	> 20 %	11.6 ± 7.6 (*n* = 7, 50–100 cm)[k]	651 (92 %)	8
First terrace	7117[g]	60 m	31 %[k]	Continuous (90 %)	> 20 %	29.9 ± 15.1 (*n* = 22, 50–100 cm)[k]	351 (92 %)	10
Second terrace	9120[g]	60 m[b]	31 %[k]	Continuous (90 %)	> 20 %	8.3 ± 6.9 (*n* = 3, 0–409 cm)[j]	450 (92 %)	4
Third terrace	2560[g]	40 m[f]	NA[o]	Continuous (90 %)	> 20 %	8.3 ± 6.9[n]	97 (90 %)	0.8
Mackenzie	13 000	48 m[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	6600	54 m[l]	36 %[l]	Continuous (90 %)	> 20 %	25.8 ± 18.8[l]	285 (91 %)	7
Indigirka	5000	54 m[l]	36 %[l]	Continuous (90 %)	> 20 %	25.8 ± 18.8[l]	216 (91 %)	5
Yenisey	4500	54 m[l]	36 %[l]	Continuous (90 %)	10–20 % (15 %)	25.8 ± 18.8[l]	201 (91 %)	5
Kolyma	3200	54 m[l]	36 %[l]	Continuous (90 %)	> 20 %	25.8 ± 18.8[l]	138 (91 %)	4
Ob	3200	54 m[l]	36 %[l]	Continuous (90 %)	10–20 % (15 %)	25.8 ± 18.8[l]	143 (91 %)	4
Pechora	3200	54 m[l]	36 %[l]	Continuous (90 %)	< 10 %	25.8 ± 18.8[l]	148 (90 %)	4
Yukon	3000	54 m[l]	36 %[l]	Continuous (90 %)	10–20 % (15 %)	25.8 ± 18.8[l]	134 (91 %)	3
Pyasina	1000	54 m[l]	36 %[l]	Continuous (90 %)	> 20 %	25.8 ± 18.8[l]	43 (91 %)	1
Colville	600	54 m[l]	36 %[l]	Continuous (90 %)	< 10 %	21.2 ± 3.8 (*n* = 4, 55–270 cm)[m]	28 (90 %)	0.6
Olenek	500	54 m[l]	36 %[l]	Continuous (90 %)	> 20 %	25.8 ± 18.8[l]	22 (91 %)	0.5
Sum/mean ±95 %/99 % CI	75 800 km^2	54 m	34 %	83 %	19 %	26.0 ± 3.1/4.1	3514 (84 %)	91 ± 39/52[p]

[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 %/99 % CI ranges are the added sum of uncertainty from estimates of mean alluvium SOC content (±11/15 Pg) and from estimates of mean alluvium depth (±28/37 Pg).

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

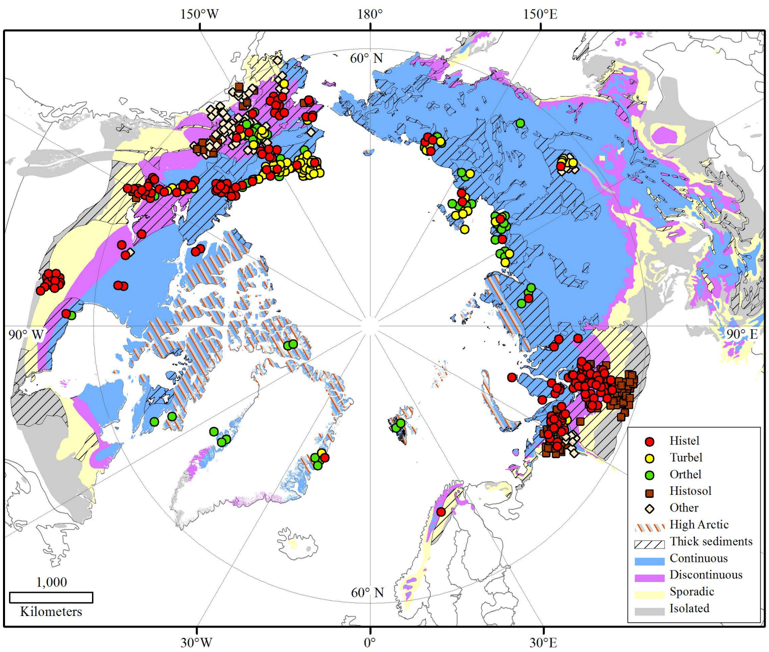

Fig. 1. Geographical distribution of regions with thick sedimentary overburden and permafrost zonation in the northern circumpolar permafrost region (Brown et al., 2002). Map shows pedon locations with data in the 0–3 m depth range (pedon dataset v2) grouped according to NCSCDv2 upscaling classes. Exact pedon locations have been manipulated for cartographic representation; projection: Azimuthal Equidistant, datum: WGS84. Adapted from Hugelius et al. (2013a).

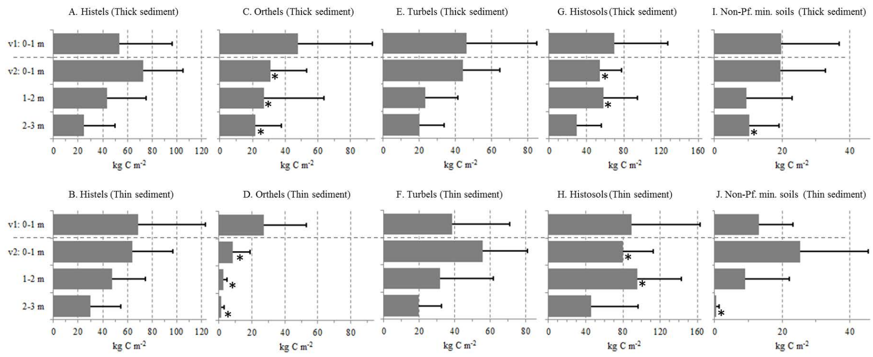

Fig. 2. Mean SOC storage (kg C m^{-2}, with error bars showing StD), subdivided by physiographic regions, for different soil upscaling classes calculated using pedon datasets v1 and v2. Different panels **(A)** to **(J)** show estimates for the 0–1 m (pedon datasets v1 and v2), 1–2 m and 2–3 m (pedon dataset v2) depth ranges in areas of thick and thin sedimentary overburden respectively. In panels **(I)** and **(J)**, the StD for v1 0–1 m is calculated from the StD of non-permafrost mineral soil orders in Table S1 of the Supplement, weighted for the total SOC mass of each soil order. Asterisks mark depth intervals in soil upscaling classes where SOC storage is significantly different from the equivalent interval in the other region (t test, $p < 0.05$).

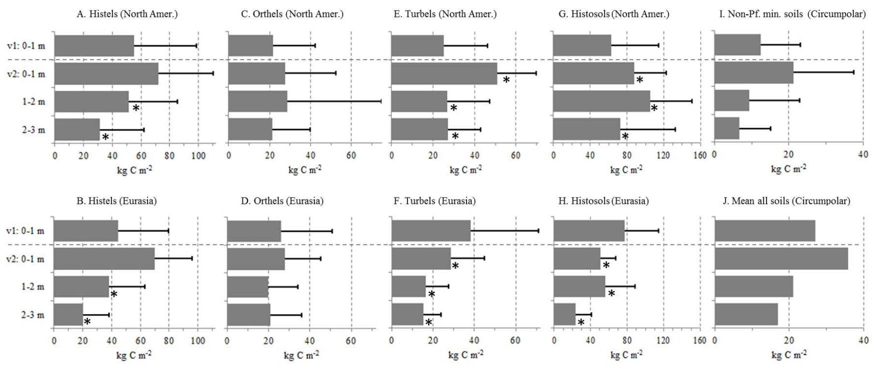

Fig. 3. Mean SOC storage (kg C m^{-2}, with error bars showing StD), subdivided by continents, for different soil upscaling classes calculated using pedon datasets v1 and v2. Different panels **(A)** to **(H)** show estimates for the 0–1 m (pedon datasets v1 and v2), 1–2 m and 2–3 m (pedon dataset v2) depth ranges in the North American and Eurasian regions. Panel **(I)** shows estimated mean circumpolar SOC storage for all non-permafrost mineral soil orders (StD for v1 0–1 m is calculated from the StD of non-permafrost mineral soil orders in Table S1 of the Supplement, weighted for the total SOC mass of each soil order). Panel **(J)** shows circumpolar SOC storage estimated from the upscaled NCSCDv2 SOC stocks, as calculated with the two pedon datasets. Asterisks mark depth intervals in soil upscaling classes where SOC storage is significantly different from the equivalent interval in the other region (t test, $p < 0.05$).

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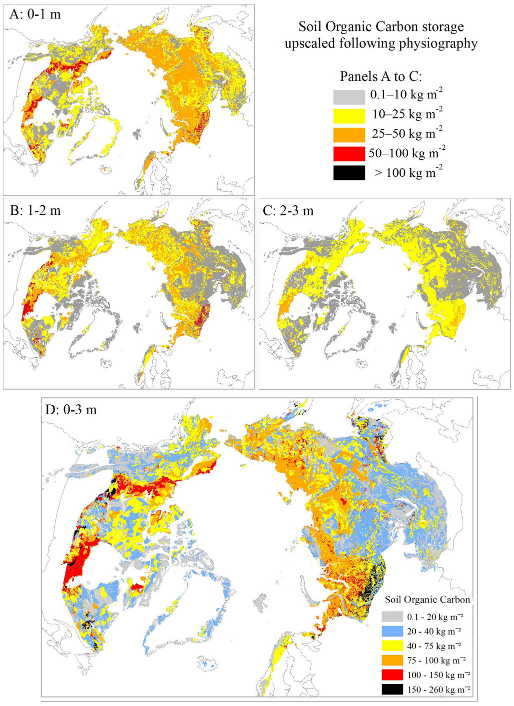

Fig. 4. Map of estimated 0–3 m SOC storage (kg C m^{-2}) in the northern circumpolar permafrost region. Shows estimates based on sediment thickness upscaling. Panels show 0–1 m SOC calculated subdivided following NCSCD regions while 1–2 m and 2–3 m SOC is calculated subdivided for Eurasia vs. North America and areas of thick vs. thin sediments, respectively. Projection: Azimuthal Equidistant, datum: WGS84.

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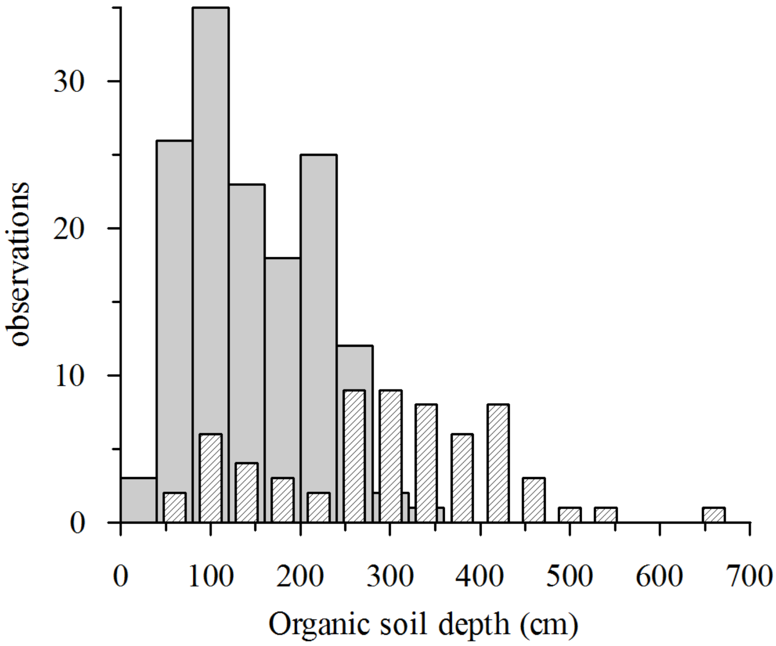

Fig. 5. Histograms illustrating the depth distribution of peat deposits (organic soil material) in Histosols and Histels of pedon dataset v2 (bins = 40 cm). The graph shows separate histograms for pedons that were gap-filled and/or extrapolated (wide gray bars) and pedons where no gap-filling and/or extrapolation was needed (narrow striped bars).

Online supplemental material for:

Improved estimates show large circumpolar stocks of permafrost carbon while quantifying substantial uncertainty ranges and identifying remaining data gaps

Hugelius[1], Strauss[2], Zubrzycki[3], Harden[4], Schuur[5], Ping[6], Schirrmeister[2], Grosse[2], Michaelson[6], Koven[7], O'Donnell[8], Elberling[9], Mishra[10], Camill[11], Yu[12], Palmtag[1] and Kuhry[1].

Submitted to Biogeoscience

1 Methods

Below is a more exhaustive and detailed description of methods. There is some overlap with the text of the main paper. The description included here is meant to be understandable on its own, without the need to refer to the main text.

1.1 Calculating 0–3 m SOC stocks

Calculation of SOC stocks based on thematic soil maps is done in three steps (Hugelius, 2012). First, the SOC storage (area-normalized SOC given in kg C m^{-2}) for individual pedons (a pedon is a described/classified and sampled three-dimensional body of soil) is calculated to the selected reference depths. Second, the pedon data is grouped into suitable thematic upscaling classes and mean SOC storage (kg C m^{-2}) for each class and reference depth is calculated. Finally, the mean SOC storage (kg C m^{-2}) of each class is multiplied with estimates of the areal coverage of thematic upscaling classes to calculate absolute SOC stocks (kg C) for different classes and reference depths.

For this study, SOC stocks were estimated separately for the 0–0.3 m, 0–1 m, 1–2 m and 2–3 m depth ranges (measured from the top of the genetic O-soil horizon, excluding litter and the living capitula of mosses) using the NCSCDv2. The NCSCDv2 is a polygon-based digital database adapted for use in Geographic Information Systems (GIS) which has been compiled from harmonized regional soil classification maps. Map data on soil coverage has been linked to pedon data with SOC storage (kg C m^{-2}) from the northern permafrost regions to estimate geographically upscaled total SOC stocks (Hugelius et al., 2013b).

1.1.1 Regional geographic subdivisions in upscaling

The SOC stocks estimates for the 0–0.3 m and 0–1 m depth ranges were calculated separately in each NCSCDv2-region (Alaska, Canada, Contiguous USA, Europe, Greenland, Iceland, Kazakhstan, Mongolia, Russia and Svalbard) following the methodology of Tarnocai et al. (2009).

In recognition of the limited soil development at high latitudes, thin soils in the High Arctic bioclimatic region were upscaled separately. The High Arctic region was defined as areas where subzones A, B and C in the Circumpolar Arctic vegetation map (Walker et al., 2005) overlap with regions of thin sedimentary overburden (Brown et al., 1997; 2002). Soil polygons in the NCSCDv2 that had their centroid within this bioclimatic region and had thin sedimentary overburden were selected (final manual editing was performed to include soil polygons in the NCSCDv2 that were clearly within the High Arctic zone but that fell outside the extent of the Circumpolar Arctic vegetation map). SOC stocks in these High Arctic soil polygons were upscaled separately across the 0–0.3 m, 0–1 m, 1–2 m and 2–3 m depth ranges.

Outside the High Arctic, we calculated two different estimates of 1–3 m SOC stocks based on separate geographical subdivisions. In the first estimate the NCPR was separated into the North American sector (includes Alaska, contiguous USA, Canada and Greenland) and the Eurasian sector (includes Europe, Iceland, Kazakhstan, Mongolia, Russia and Svalbard), respectively.

For the second estimate, pedons and mapped soil areas in the NCPR were separated into areas of thick and thin sedimentary overburden (Fig. 1). The spatial extent of the NCPR is defined following the “Circum-Arctic map of permafrost and ground-ice conditions” (Brown et al., 1997; 2002). The spatial base and first order classification criterion used to create this map were regional physiographic or landscape maps (Heginbottom et al., 1993). Based on these regional maps, numerous published data sources and input from regional experts, the NCPR was subdivided into two broad classes (Heginbottom et al., 1993): (1) “areas of lowlands, highlands and intra- and inter-montane depressions characterized by thick overburden, wherein ground ice is expected to be generally fairly extensive” and (2) “areas of mountains, highlands, and plateaus characterized by thin overburden and exposed bedrock, where generally lesser amounts of ground ice are expected to occur” (thick overburden is defined as >5–10 m).

1.1.2 Thematic subdivisions of soil classes in upscaling

The upscaled SOC stock estimates for the 0–0.3 m and 0–1 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 sub-orders: Turbels (cryoturbated permafrost soils), Histels (organic permafrost soils) and Orthels (non-cryoturbated permafrost-affected mineral soils).

For the 1–2 m and 2–3 m depth ranges, a reduced thematic resolution 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. For the continent based upscaling (separating North America and Eurasia) the non-permafrost mineral soils were merged to the whole NCPR because of a lack of pedon data in the Eurasian region.

In the High Arctic region, low data availability led us to reduce the thematic resolution so that the three Gelisol suborders were combined into one class. For parts of the NCPR located outside of North America, the 0–0.3 m and 0–1 m depth SOC stocks in the NCSCDv2 are calculated from SOC data generalized over large regions (Hugelius et al., 2013b). The same mean SOC storage (kg C m^{-2}) values were used within soil classes across the full latitudinal ranges in Europe, Greenland, Iceland, Russia, Mongolia, Kazakhstan and Svalbard (Tarnocai et al., 2009). Because of this, new values to estimate 0–0.3 m and 0–1 m depth SOC storage (kg C m^{-2}) in the High Arctic parts of these regions were derived from pedon data presented by Hugelius et al. (2013a).

1.1.3 Pedon databases and calculation of SOC content

The mean SOC storage (kg C m^{-2}) used in this study to estimate total SOC stocks for near surface soils (0–0.3 m and 0–1 m depth ranges) are derived from the same pedon database that was used by Tarnocai et al. (2009), but the GIS-database has been gap-filled for missing data (both missing soil map polygons and missing calculated SOC stock data in some polygons) and updated calculations of soil area have been done following gap-filling. These

SOC storage (kg C m^{-2}) values are based on 1778 individual pedons from around the NCPR (mainly Gelisol and Histosol pedons), that have been complemented with SOC storage (kg C m^{-2}) data from Batjes (1996) where data for non-permafrost soil orders was missing (this pedon dataset is hereafter called pedon dataset v1). More detailed information regarding this pedon dataset, including details regarding which soil orders were supplemented 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 0–0.3 and 0–1 m SOC stocks we refer to Hugelius et al. (2013b).

For the deeper soil layers (1–2 m and 2–3 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 v2). Table 1 summarizes the number of individual pedons available from different geographical regions and areas of thick/thin sedimentary overburden. More detailed information regarding this pedon dataset can be found in table S1 of the supplementary online materials. Pedon dataset v2 includes a large number of pedons that were gap-filled using extrapolated and/or estimated values of bulk density and/or percentage organic carbon content (OC%) (Hugelius et al., 2013a). This applies particularly to organic soils (Histels and Histosols) where the database also includes all available pedons with O-horizons ≥40 cm, but that lacked full deep characterization. In these cases, to estimate SOC storage in the underlying mineral subsoil, data from mineral soil genetic C-horizons (i.e. bulk density and OC%) were extrapolated to the full 3 m baseline depth (or default values from other similar sites were used). These extensive extrapolations are used to avoid a sampling bias towards deep peat deposits in the database, which would lead to significant overestimation of deep (>1 m) SOC stocks in organic soils. For full data-access and further details regarding the compilation, gap-filling procedures etc. for pedon dataset v2 we refer to Hugelius et al (2013a).

Because different pedon datasets were used to calculate 0–1 m SOC stocks (pedon dataset v1) and 1–3 m SOC stocks (pedon dataset v2), there was a concern that these two dataset may not accurately reflect the same statistical populations (Hugelius, 2012). Therefore, the circumpolar mean 0–1 m SOC storage (kg C m-2) between the two databases was compared using Student's t-test (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 v1, the tests could not be done separately for North America / Eurasia or areas of thick / thin sedimentary overburden (mean, standard deviation and n values of pedon dataset v1 for the separate regions are not known). For each soil upscaling class (reduced thematic resolution), SOC storage (kg C m^{-2}) in the individual depth ranges (0–1 m, 1–2 m and 2–3 m) were also compared across regions (North America vs. Eurasia) and deposit-thickness classes (thick sediments vs. thin sediments) using Student's t-test.

1.2 Calculating deltaic SOC stocks

The approach used to estimate deltaic SOC stocks in this study 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 storage (kg C m^{-3}) from the Mackenzie River Delta (Canada) combined with data on the spatial coverage of seven large arctic deltas. For the calculation presented here we combine 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 is calculated from the mapped sub-aerial deltas extent and the mean depth of alluvial deposits, subtracting the volume that is estimated to be occupied by massive ice and water bodies. To avoid double counting, the top 3 m of soil as well as known Yedoma deposits located in the Lena Delta are removed from the calculation. When the total volume of alluvium is calculated, the total SOC pool of each delta is estimated using field data of mean alluvium SOC storage (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.

Walker (1998) provides a baseline estimate of the sub-aerial spatial extent of major Arctic river deltas. We selected this reference for our estimate of delta spatial extent, and included those deltas that are located within the NCPR. Because of the distinct geological histories and general characteristics of the main terraces of the Lena River Delta (Russia) we divided this delta into three terraces and the recent floodplain based on previous research (Grigoriev, 1993; Schwamborn et al., 2002; Zubrzycki et al., 2013). Estimates of the fraction of delta surfaces covered by water bodies were available for the Mackenzie River Delta (Smith, 2011) and the Lena River Delta (Morgenstern et al., 2008; 2011).

Estimated permafrost extent and massive ice-content in deltaic deposits were extracted from the Circum-Arctic map of permafrost and ground-ice conditions (Brown et al., 2002). Because this product maps massive ice occurrence in the upper 10–20 m of sediment, the mapped massive ice is assumed to extend through the upper 15 m of alluvium (we assume zero massive ice-content below this depth). Schwamborn et al. (2002) show that a talik ca. 95 m deep is developed underneath Lake Nikolay on Arga Island (Lena River Delta). Also, Burn (2002) found that most lakes in the Mackenzie River Delta that exceed critical areal-thresholds (18%–27% of all delta lakes) have taliks that extend through the permafrost while littoral margins under shallow water generally have permafrost in the upper few meters. Because of this evidence of taliks below deltaic water-bodies, unfrozen alluvium is assumed to occur primarily under water bodies for the purposes of our calculations.

Tarnocai et al. (2009) used a 5 m mean depth of delta water-bodies to calculate the volume of water. Boike et al. (2013) report that depths of polygonal ponds on Samoylov Island (Lena Delta, Russia) range from a few cm up to 1.3 m while inventoried thermokarst lakes are up to 6.1 m deep. In the 2nd terrace of the Lena River Delta, lakes reach depths of up to 10–30 m, but large lake expanses are typically <2 m deep (Schwamborn et al., 2002). Field measurements based on ground penetrating radar in the Middle Channel of the Mackenzie River Delta show a maximum depth of ca. 5 m at one location (Stevens et al., 2009). Burn (2002) reports maximum depths from twelve inventoried lakes on Richards Island (Mackenzie River Delta) ranging from 2.1–13.1 m. Water depths in delta water bodies are highly variable and expected to range outside of the values reported above. Because no comprehensive summative data regarding the mean depth of water bodies on delta surfaces is available we also use a mean depth of 5 m for this study.

Field data on mean alluvial SOC content (kg C m^{-3}) were available from the Mackenzie River Delta (Tarnocai et al., 2009), the Lena River Delta (Zubrzycki et al., 2013, Schirrmeister et al., 2011b) and the Colville River Delta in Alaska (Ping et al., 2011). When calculating mean alluvium SOC storage (kg C m^{-3}), near surface soil horizons showing organic C enrichment from ongoing/recent soil formation were excluded from calculations. Buried organically enriched soil horizons were included in calculations. Much of the available data for calculating alluvium SOC storage is from near surface deposits but we extrapolate this data to the full depth of alluvium, based on an assumption that these alluvium deposits are relatively homogenous across depths.

1.3 Calculating Yedoma region permafrost SOC stocks

For the purpose of these calculations, the Yedoma region is subdivided into areas of intact Yedoma deposits (late Pleistocene ice- and organic-rich silty sediments) and permafrost deposits formed in thaw-lake basins (generalized as thermokarst deposits). Areas 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 for depths >3 m are calculated based on individual observations of: deposit thickness (n=20 and 8, respectively), organic C (weight %, n=682 and 219), bulk density (n=428 and 117), and wedge-ice (volume %, n=10 and 6). For details regarding calculations of the spatial extent of different sediments, data collection and spatial distribution of field observations we refer to 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 (10,000 times) observed values (following methodology of Strauss et al. 2013). After bootstrapping the populations of observations, the total mean pool size estimate was derived from these 10,000 bootstrap samples afterward. Because organic C % and bulk density of individual sediment samples are auto-correlated, paired values were used in the resampling process.

1.4 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 (i) database errors which are uncertainties caused by insufficient field-data representation to describe natural soil variability within an upscaling class and (ii) spatial errors which are uncertainties caused by areal misrepresentation of classes in the upscaling map (Hugelius, 2012). The former 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; however, this procedure assumes that the available sample accurately reflects the natural variability within a class. The latter 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 assume that the spatial extent of different soil orders, deltas and the Yedoma region within the NCPR are correctly mapped.

1.4.1 Uncertainties of SOC estimates in 0–3 m soils and deltaic deposits

In the present study, we assessed pedon database errors for the different soil depth ranges and the deltaic deposits by calculating confidence interval (CI) ranges for the total landscape estimates in the different regions. These CI ranges are calculated from the variance and proportional areal/volumetric contribution of each upscaling class i, using the formula (Thompson, 1992):

$$CI= t\times\sqrt{(\sum((a_i^2\times StD_i^2) / n_i))} \qquad (1)$$

where: t is the upper α/2 of a normal distribution (t≈1.96 for a 95% CI and t≈2.58 for a 99% CI), a_i = percentage of the total area/volume for class i, StD_i= standard deviation of the class i, n_i = number of replicates in class i. For the estimates of near surface soils (0–0.3 m and 0–1 m), the calculation was done for the whole NCPR, using mean SOC stocks calculated from the NCSCDv2 and values of StD (translated to the NCSCDv2 means by using the coefficient of variation) and n from Tarnocai et al. (2009) and Batjes (1996). All data used to calculate the different CI ranges are summarized in table S1 of the supplementary online materials.

For each separate delta, calculations of upscaling uncertainties from variability in estimated alluvium SOC storage (kg C m^{-3}) as well as variability in estimated depth of alluvium were done. When estimating variance of alluvium depth data for individual deltas, the coefficient of variation was assumed to be at least equal to that of the Mackenzie Delta. Multiple depth observations are only available for the Mackenzie Delta and it is assumed that estimates for other deltas would be equally variable.

1.4.2 Uncertainties of SOC estimates in Yedoma region deposits

The observation-based bootstrapping method used to estimate SOC stocks in the Yedoma region is inherently very different from the approach used to calculate uncertainty in the other SOC stock estimates. This bootstrapping approach allows calculating a full propagation of the data uncertainty through the inventory calculation (assuming that the areal extent of the region is correctly estimated). The uncertainty ranges presented in this study are the 16^{th} and

84th percentiles of bootstrapped observations (following Strauss et al., 2013). This uncertainty mirrors the data uncertainty, not only the uncertainty of the mean estimator. To fully estimate the estimator's (observation-based mean) uncertainty, several independent bootstrapping runs, with mean calculation in each case, would be necessary. On the one hand, because single value estimates reduces the variability, a smaller uncertainty range would be inferred with this approach. But on the other hand, the described and applied conservative uncertainty approach, using a single bootstrapping run, is closer to the natural inherent heterogeneity of the dataset. Computations were performed using the open source software R (boot package).

1.4.3 Combining confidence intervals/uncertainty estimates

Combined propagated uncertainty ranges when summing up the different depth ranges ($CI_{0–1\ m}+CI_{1–2\ m}$ etc.) or different components ($CI_{0–3\ m} + CI_{delta}$ etc.) of the total NCPR SOC stocks were calculated in two ways:

1. ($_{add}CI$) by addition of the relative CI ranges of different components (CI_x+CI_y etc.).

2. ($_{cov}CI$) by using a formula for additive error propagation of covarying variables (Roddick, 1987):

$$_{cov}CI=\sqrt{(CI_x^2\times CI_y^2+2\rho xyCI_xCI_y)} \quad (2)$$

Where ρxy is the correlation coefficient of variables x and y. The summative calculations were done in several steps, first the correlation coefficient between 0–1 m and 1–2 m SOC storage (kg C m^{-2}) in pedon spreadsheet v2 ($\rho=0.58$, $p<0.05$) was used to calculate covCI for the 0–2 m SOC stocks. In a second step the correlation coefficient between 0–2 m and 2–3 m SOC storage (kg C m^{-2}) in pedon spreadsheet v2 ($\rho=0.41$, $p<0.05$) was used to calculate covCI for the 0–3 m SOC stocks. For the purpose of these calculations SOC storage in the 0–3 m depth range is assumed to be uncorrelated to Yedoma region and deltaic SOC storage.

2 Results

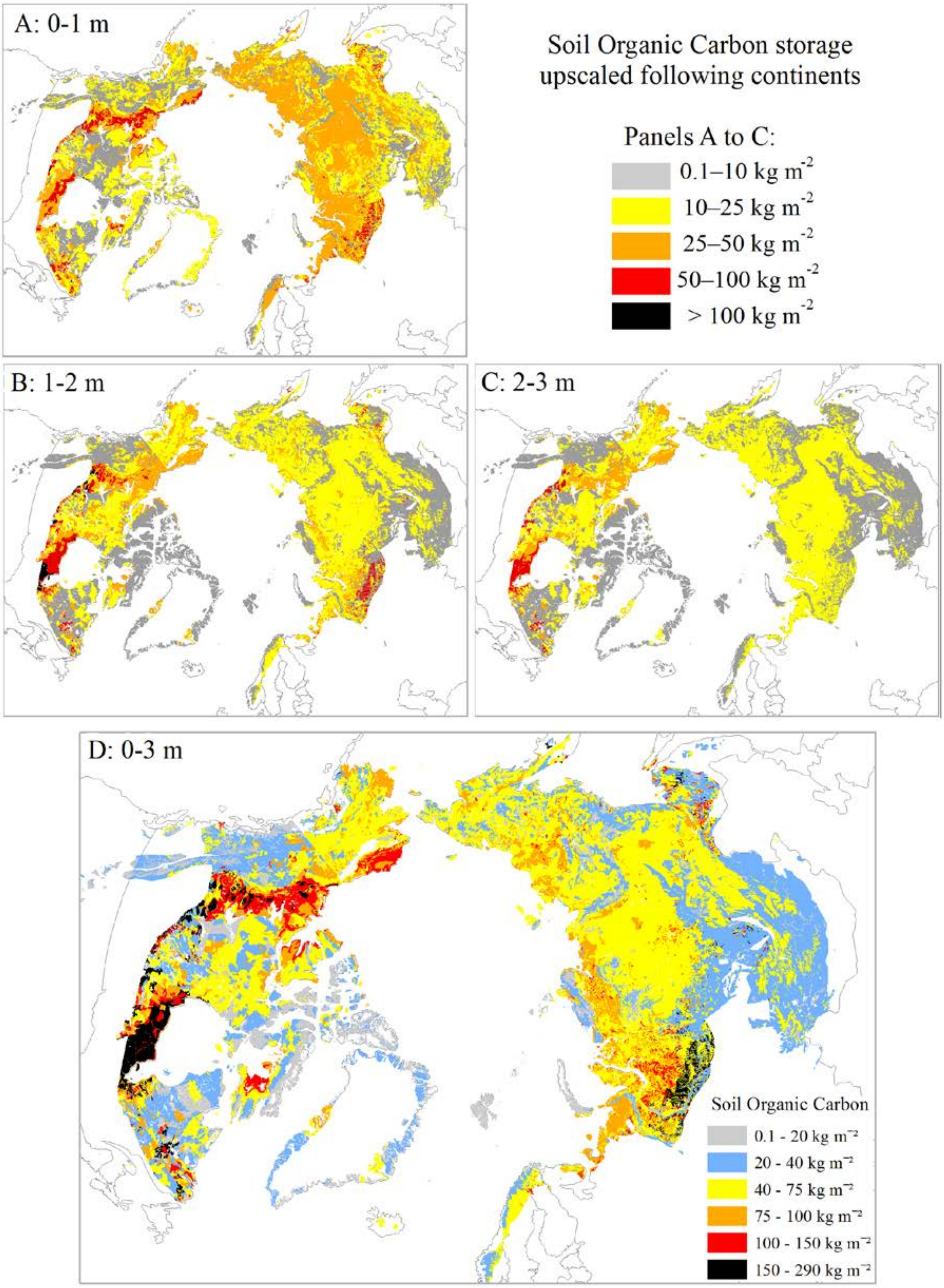
A: 0-1 m
Soil Organic Carbon storage
upscaled following continents
Panels A to C:
0.1–10 kg m^{-2}
10–25 kg m^{-2}
25–50 kg m^{-2}
50–100 kg m^{-2}
> 100 kg m^{-2}
B: 1-2 m
C: 2-3 m
D: 0-3 m
Soil Organic Carbon
0.1 - 20 kg m^{-2}
20 - 40 kg m^{-2}
40 - 75 kg m^{-2}
75 - 100 kg m^{-2}
100 - 150 kg m^{-2}
150 - 290 kg m^{-2}

Figure S1. Maps of estimated SOC storage in the northern circumpolar permafrost region. Panels show 0–1 m SOC storage (kg C m^{-2}) calculated subdivided following NCSCD regions while 1–2 m and 2–3 m SOC is calculated subdivided for Eurasia vs North America and areas of thick vs thin sediments, respectively. Projection: Azimuthal Equidistant, datum: WGS84.

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