

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.

5 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).

10 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).

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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 perennally 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).

10 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 $\times 11$ for 1–2 m soils, a factor $\times 8$ for 2–3 m soils and deltaic alluvium and a factor $\times 5$ 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 subdivision 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).

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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 processes 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

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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 perennally frozen alluvium are 69 ± 34 Pg (95 % addCI).

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 km². Of this 416 000 km² (30 %) is considered intact Yedoma and 775 000 km² (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 km²) and areas covered by deltaic or fluvial sediments (47 000 km²) 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 perennally frozen thermokarst basin deposits.

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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

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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).

5 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).

25 Because of their substantial areal extent and high mean SOC storage (kgCm^{-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 (kgCm^{-2}) across regions.

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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.

5 The mean SOC storage (kgCm^{-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 (kgCm^{-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.

10 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)

25 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 permafrost 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.

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

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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 dataset 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 (kgC 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

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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

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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 $\sim 65\,000\text{ km}^2$ 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 on 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 $\pm 8\%$ 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

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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 $> 3\text{ m}$ 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 $> 3\text{ m}$ 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, $6.2 \times 10^6\text{ km}^2$ of the permafrost region is characterized by thick sedimentary overburden (sediments $> 5\text{--}10\text{ m}$ thick; Brown et al., 2002). Deltaic deposits and the Yedoma region included in this study

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together cover ca. $1.5 \times 10^6 \text{ km}^2$. Any SOC stored in deposits $> 3 \text{ m}$ depth in the remaining ca. $5 \times 10^6 \text{ km}^2$ 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 wild-fire (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 susceptible to decomposition in the unfrozen phase (O'Donnell et al., 2011).

Global scale projections of greenhouse-gas emissions from permafrost deposits using Earth System Models (ESMs) demonstrate that inclusion of permafrost soil C stocks lead to the potential for a large positive climate feedback from the permafrost region (Koven et al., 2011; Schaefer et al., 2011; Burke et al., 2012; Schneider von Deimling et al., 2012; MacDougall et al., 2012). These models are still simplified representations of permafrost carbon cycling and do not resolve high landscape spatial

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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 $\times 8$ – 11 for 1–3 m soils, a factor $\times 8$ for deltaic alluvium and a factor $\times 5$ for Yedoma region deposits.

The updated estimates of permafrost region SOC stocks are $217 \pm 15 \text{ Pg}$ for 0–0.3 m depth and $473 \pm 34 \text{ Pg}$ for 0–1 m depth ($\pm 95\% \text{ CI}$). Estimates for 0–3 m SOC storage are $1034 \pm 183 \text{ Pg}$, with $> 1 \text{ m}$ 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 $1104 \pm 133 \text{ Pg}$. Of this, $34 \pm 16 \text{ Pg C}$ 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 twelve ma-
5 jor 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 con-
siderably (Tarnocai et al., 2009). In permafrost sediments of the Yedoma region, esti-
10 mated > 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 re-
gions 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
15 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 occurring across this region. An estimated mean stor-
age 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
15 (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 sub-
stantial regional gaps in pedon data to assess > 1 m SOC storage. Especially cryotur-
bated soils and organic soil orders are highly variable and difficult to assess. The High
20 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.
25 1×10^6 km²). 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 limi-
tations 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 over-
burden areas, and (3) sampling soils away from current data clusters, particularly in

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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
5 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
10 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.

15 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
20 **[http://www.biogeosciences-discuss.net/11/4771/2014/
bgd-11-4771-2014-supplement.zip](http://www.biogeosciences-discuss.net/11/4771/2014/bgd-11-4771-2014-supplement.zip)**.

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References

- Aylsworth, J. M., Burgess, M. M., Desrochers, D. T., Duk-Rodkin, A., Robertsson, T., and Traynor, J. A.: Surficial geology, subsurface materials and thaw sensitivity of sediments, in: The Physical Environment of the Mackenzie Valley, Northwest Territories: a Base Line for the Assessment of Environmental Change, edited by: Dyke, L. D. and Brooks, G. R., Geological Survey of Canada, Bulletin, 547, 31–39, 2000.
- Batjes, N. H.: Total carbon and nitrogen in the soils of the world, *Eur. J. Soil Sci.*, 47, 151–163, 1996.
- Brown, J., Ferrians Jr., O. J., Heginbottom, J. A., and Melnikov, E. S.: Circum-Arctic map of permafrost and ground-ice conditions, 1 : 10000000, Map CP-45, United States Geological Survey, International Permafrost Association, Washinton D.C., USA, 1997.
- Brown, J., Ferrians Jr., O. J., Heginbottom, J. A., and Melnikov, E. S.: Circum-Arctic Map of Permafrost and Ground-Ice Conditions, version 2, National Snow and Ice Data Center, Boulder, Colorado, USA, 2002.
- Burke, E. J., Hartley, I. P., and Jones, C. D.: Uncertainties in the global temperature change caused by carbon release from permafrost thawing, *The Cryosphere*, 6, 1063–1076, doi:10.5194/tc-6-1063-2012, 2012.
- Davidson, E. A. and Janssens, I. A.: Temperature sensitivity of soil carbon decomposition and feedbacks to climate change, *Nature*, 440, 165–173, 2006.

4805

- Grigoriev, M. N.: Cryomorphogenesis in the Lena Delta, Permafrost Institute Press, Yakutsk, 176 pp., 1993 (in Russian).
- Grosse, G., Harden, J., Turetsky, M., McGuire, A. D., Camill, P., Tarnocai, C., Frolking, S., Schuur, E. A. G., Jorgenson, T., Marchenko, S., Romanovsky, V., Wickland, K. P., French, N., Waldrop, M., Bourgeau-Chavez, L., and Striegl, R. G.: Vulnerability of high-latitude soil organic carbon in North America to disturbance, *J. Geophys. Res.*, 116, G00K06, doi:10.1029/2010JG001507, 2011.
- Grosse, G., Robinson, J. E., Bryant, R., Taylor, M. D., Harper, W., DeMasi, A., Kyker-Snowman, E., Veremeeva, A., Schirrmeister, L., and Harden, J.: Distribution of late Pleistocene ice-rich syngenetic permafrost of the Yedoma Suite in east and central Siberia, Russia, US G. S. Open File Report, 1078, 37, Washinton D.C., USA, 2013.
- Harden, J. W., Trumbore, S. E., Stocks, B. J., Hirsch, A., Gower, S. T., O'Neill, K. P., and Kasischke, E. S.: The role of fire in the boreal carbon budget, *Glob. Change Biol.*, 6, 174–184, doi:10.1046/j.1365-2486.2000.06019.x, 2000.
- Harden, J. W., Meier, R., Silapaswan, C., Swanson, D. K., and McGuire, A. D.: Soil drainage and its potential for influencing wildfires in Alaska, in: Studies by the US Geological Survey in Alaska, 2001, edited by: Galloway, J., US Geological Survey Professional Paper 1678, 139–144, Washinton D.C., USA, 2003.
- Harden, J. W., Manies, K. L., Turetsky, M. R., and Neff, J. C.: Effects of wildfire and permafrost on soil organic matter and soil climate in interior Alaska, *Glob. Change Biol.*, 12, 2391–2403, 2006.
- Harden, J. W., Koven, C. D., Ping, C.-L., Hugelius, G., David McGuire, A., Camill, P., Jorgenson, T., Kuhry, P., Michaelson, G. J., O'Donnell, J. A., Schuur, E. A. G., Tarnocai, C., Johnson, K., and Grosse, G.: Field information links permafrost carbon to physical vulnerabilities of thawing, *Geophys. Res. Lett.*, 39, L15704, doi:10.1029/2012GL051958, 2012.
- Heginbottom, J. A.: Permafrost distribution and ground ice in surficial materials, in: The Physical Environment of the Mackenzie Valley, Northwest Territories: a Base Line for the Assessment of Environmental Change, edited by: Dyke, L. D., and Brooks, G. R., Geological Survey of Canada Bulletin, 547, 31–39, 2000.
- Heginbottom, J. A., Brown, J., Melnikov, E. S., and Ferrians, O. J.: Circumarctic map of permafrost and ground ice conditions, Sixth International Conference on Permafrost, Beijing, Proceedings, Wushan, Guangzhou, China, South China University Press, vol. 2, 1132–1136, 5–9 July, 1993.

4806

- Horwath Burnham, J. and Sletten, R. S.: Spatial distribution of soil organic carbon in northwest Greenland and underestimates of high Arctic carbon stores, *Global Biogeochem. Cy.*, 24, GB3012, doi:10.1029/2009GB003660, 2010.
- Houghton, R. A.: Balancing the global Carbon Budget, *Annu. Rev. Earth Planet. Sci.*, 35, 313–347, 2007.
- Hugelius, G.: Spatial upscaling using thematic maps: an analysis of uncertainties in permafrost soil carbon estimates, *Global Biogeochem. Cy.*, 26, GB2026, doi:10.1029/2011GB004154, 2012.
- Hugelius, G. and Kuhry, P.: Landscape partitioning and environmental gradient analyses of soil organic carbon in a permafrost environment, *Global Biogeochem. Cy.*, 23, GB3006, doi:10.1029/2008GB003419, 2009.
- Hugelius, G., Virtanen, T., Kaverin, D., Pastukhov, A., Rivkin, F., Marchenko, S., Romanovsky, V., and Kuhry, P.: High-resolution mapping of ecosystem carbon storage and potential effects of permafrost thaw in periglacial terrain, *European Russian Arctic, J. Geophys. Res.*, 116, G03024, doi:10.1029/2010JG001606, 2011.
- Hugelius, G., Routh, J., Kuhry, P., and Crill, P.: Mapping the degree of decomposition and thaw remobilization potential of soil organic matter in discontinuous permafrost terrain, *J. Geophys. Res.*, 117, G02030, doi:10.1029/2011JG001873, 2012.
- Hugelius, G., Tarnocai, C., Broll, G., Canadell, J. G., Kuhry, P., and Swanson, D. K.: The Northern Circumpolar Soil Carbon Database: spatially distributed datasets of soil coverage and soil carbon storage in the northern permafrost regions, *Earth Syst. Sci. Data*, 5, 3–13, doi:10.5194/essd-5-3-2013, 2013a.
- Hugelius, G., Bockheim, J. G., Camill, P., Elberling, B., Grosse, G., Harden, J. W., Johnson, K., Jorgenson, T., Koven, C. D., Kuhry, P., Michaelson, G., Mishra, U., Palmtag, J., Ping, C.-L., O'Donnell, J., Schirrmeyer, L., Schuur, E. A. G., Sheng, Y., Smith, L. C., Strauss, J., and Yu, Z.: A new data set for estimating organic carbon storage to 3 m depth in soils of the northern circumpolar permafrost region, *Earth Syst. Sci. Data*, 5, 393–402, doi:10.5194/essd-5-393-2013, 2013b.
- Johnston, G. H. and Brown, R. J. E.: Stratigraphy of the Mackenzie River Delta, Northwest Territories, Canada, *Geol. Soc. Am. Bull.*, 76, 103–112, 1965.
- Johnson, K. D., Harden, J. W., McGuire, A. D., Bliss, N. B., Bockheim, J. G., Clark, M., Nettleton-Hollingsworth, T., Jorgenson, M. T., Kane, E. S., Mack, M., O'Donnell, J., Ping, C.,

4807

- Schuur, E. A. G., Turetsky, M. R., and Valentine, D. W.: Soil carbon distribution in Alaska in relation to soil-forming factors, *Geoderma*, 167–168, 71–84, 2011.
- Jones, B. M., Grosse, G., Arp, C. D., Jones, M. C., Walter Anthony, K. M., and Romanovsky, V. E.: Modern thermokarst lake dynamics in the continuous permafrost zone, northern Seward Peninsula, Alaska, *J. Geophys. Res.*, 116, G00M03, doi:10.1029/2011jg001666, 2011.
- Jones, B. M., Stoker, J. M., Gibbs, A. E., Grosse, G., Romanovsky, V. E., Douglas, T. A., Kinsman, N. E. M., and Richmond, B. M.: Quantifying landscape change in an arctic coastal lowland using repeat airborne LiDAR, *Environ. Res. Lett.*, 8, 045025, doi:10.1088/1748-9326/8/4/045025, 2013.
- Jorgenson, M. T., Yoshikawa, K., Kanveskiy, M., Shur, Y., Romanovsky, V., Marchenko, S., Grosse, G., Brown, J., and Jones, B.: Permafrost characteristics of Alaska, *Proceedings of the Ninth International Conference on Permafrost*, 3, 121–122, 2008.
- Kanveskiy, M., Shur, Y., Jorgenson, M. T., Ping, C.-L., Michaelson, G. J., Fortier, D., Stephani, E., Dillon, M., and Tumskey, V.: Ground ice in the upper permafrost of the Beaufort Sea coast of Alaska, *Cold Reg. Sci. Technol.*, 85, 56–70, doi:10.1016/j.coldregions.2012.08.002, 2013.
- Koven, C. D., Ringeval, B., Friedlingstein, P., Ciais, P., Cadule, P., Khvorostyanov, D., Krinner, G., and Tarnocai, C.: Permafrost carbon-climate feedbacks accelerate global warming, *Proc. Natl. Acad. Sci. USA*, 108, 14769–14774, doi:10.1073/pnas.1103910108, 2011.
- Kuhry, P., Grosse, G., Harden, J., Hugelius, G., Koven, C., Ping, C. L., Schirrmeyer, L., and Tarnocai, C.: Characterization of the Permafrost Carbon Pool, *Permafrost Periglac.*, 24, 146–155, doi:10.1002/ppp.1782, 2013.
- MacDougall, A. H., Avis, C. A., and Weaver, A. J.: Significant contribution to climate warming from the permafrost carbon feedback, *Nat. Geosci.*, 5, 719–721, doi:10.1038/NGEO1573, 2012.
- McGuire, A. D., Anderson, L. G., Christensen, T. R., Dallimore, S., Guo, L., Hayes, D. J., Heimann, M., Lorenson, T. D., Macdonald, R. W., and Roulet, N.: Sensitivity of the carbon cycle in the Arctic to climate change, *Ecol. Monogr.*, 79, 523–555, 2009.
- Michaelson, G. J., Ping, C. L., and Kimble, J. M.: Carbon storage and distribution in tundra soils of Arctic Alaska, USA, *Arctic Alpine Res.*, 28, 414–424, doi:10.2307/1551852, 1996.
- Mishra, U., Jastrow, J. D., Matamala, R., Hugelius, G., Koven, C. D., Harden, J. W., Ping, C. L., Michaelson, G. J., Fan, Z., Miller, R. M., McGuire, A. D., Tarnocai, C., Kuhry, P., Riley, W. J.,

4808

- Schwamborn, G., Andreev, A. A., Rachold, V., Hubberten, H.-W., Grigoriev, M. N., Tumskoy, V., Pavlova, E. Y., and Dorozkhina, M. V.: Evolution of Lake Nikolay, Arga Island, western Lena River delta, during late Pleistocene and Holocene time, *Polarforschung*, 70, 69–82, 2002.
- Sheng, Y., Smith, L. C., MacDonald, G. M., Kremenetski, K. V., Frey, K. E., Velichko, A. A., Lee, M., Beilman, D. W., and Dubinin, P.: A high-resolution GIS-based inventory of the west Siberian peat carbon pool, *Global Biogeochem. Cy.*, 18, GB3004, doi:10.1029/2003GB002190, 2004.
- Smith, I. R.: The seismic shothole drillers' log database and GIS for Northwest Territories and northern Yukon: an archive of near-surface lithostratigraphic surficial and bedrock geology data, Geological Survey of Canada, Open File 6833, 1 DVD-ROM, doi:10.4095/288754, 2011.
- Smith, S. L., Burgess, M. M., Chartrand, J., and Lawrence, D. E.: Borehole geotechnical database for the Mackenzie Valley/Delta region, Geological Survey of Canada Open File 4924, 2005.
- Soil Survey Staff: Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys, Agric. Handb. 436, 2nd edn., US Dep. of Agric., Washington, D.C., USA, 869 pp., 1999.
- Strauss, J., Schirrmeister, L., Wetterich, S., Borchers, A., and Davydov, S. P.: Grain-size properties and organic-carbon stock of Yedoma Ice Complex permafrost from the Kolyma lowland, northeastern Siberia, *Global Biogeochem. Cy.*, 26, GB3003, doi:10.1029/2011GB004104, 2012.
- Strauss, J., Schirrmeister, L., Grosse, G., Wetterich, S., Ulrich, M., Herzschuh, U., and Hubberten, H.-W.: The deep permafrost carbon pool of the Yedoma region in Siberia and Alaska, *Geophys. Res. Lett.*, 40, 6165–6170, doi:10.1002/2013GL058088, 2013.
- Tarnocai, C. and Stolbovoy, S.: Northern peatlands: their characteristics, development and sensitivity to climate change, in: *Peatlands: Evolution and Records of Environmental and Climate Changes*, edited by: Martini, I. P., Martinez Cortizas, A., and Chesworth, W., *Dev. Earth Surface Processes*, vol. 9, Elsevier, Amsterdam, chap. 2, 17–51, 2006.
- Tarnocai, C., Kettles, I. M., and Lacelle, B.: Peatlands of Canada Database, Research Branch, Agriculture and Agri-Food Canada, Ottawa, Ontario, Canada, digital database, 2005.
- Tarnocai, C., Canadell, J., Mazhitova, G., Schuur, E. A. G., Kuhry, P., and Zimov, S.: Soil organic carbon stocks in the northern circumpolar permafrost region, *Global Biogeochem. Cy.*, 23, GB2023, doi:10.1029/2008GB003327, 2009.

4811

- Taylor, A. E., Dallimore, S. R., and Judge, A. S.: Late Quaternary history of the Mackenzie-Beaufort Region, Arctic Canada, from modelling of permafrost temperatures, 2. The Mackenzie Delta – Tuktoyaktuk coastlands, *Can. J. Earth Sci.*, 33, 62–71, 1996.
- Turetsky, M. R., Kane, E. S., Harden, J. W., Ottmar, R. D., Manies, K. L., Hoy, E., and Kasischke, E. S.: Recent acceleration of biomass burning and carbon losses in Alaskan forests and peatlands, *Nat. Geosci.*, 4, 27–31, doi:10.1038/ngeo1027, 2011.
- Ulrich, M., Grosse, G., Strauss, J., and Schirrmeister, L.: Quantifying ice-wedge volumes in Yedoma and thermokarst deposits using remote sensing and field data, *Permafrost Periglac.*, in press, 2014.
- Walker, H. J.: Arctic deltas, *J. Coast. Res.*, 14, 718–738, 1998.
- Yi, S., Manies, K., Harden, J. W., and McGuire, A. D.: Characteristics of organic soil in black spruce forests: implications for the application of land surface and ecosystem models in cold regions, *Geophys. Res. Lett.*, 36, L05501, doi:10.1029/2008GL037014, 2009.
- Yu, Z. C.: Northern peatland carbon stocks and dynamics: a review, *Biogeosciences*, 9, 4071–4085, doi:10.5194/bg-9-4071-2012, 2012.
- Zhang, T., Barry, R. G., Knowles, K., Heginbottom, J. A., and Brown, J.: Statistics and characteristics of permafrost and ground-ice distribution in the Northern Hemisphere, *Polar Geography*, 23, 132–154, doi:10.1080/10889379909377670, 1999.
- Zimov, S. A., Davydov, S. P., Zimova, G. M., Davydova, A. I., Schuur, E. A. G., Dutta, K., and Chapin, F. S.: Permafrost carbon: stock and decomposability of a globally significant carbon pool, *Geophys. Res. Lett.*, 33, L20502, doi:10.1029/2006GL027484, 2006.
- Zubrzycki, S., Kutzbach, L., Grosse, G., Desyatkin, A., and Pfeiffer, E.-M.: Organic carbon and total nitrogen stocks in soils of the Lena River Delta, *Biogeosciences*, 10, 3507–3524, doi:10.5194/bg-10-3507-2013, 2013.

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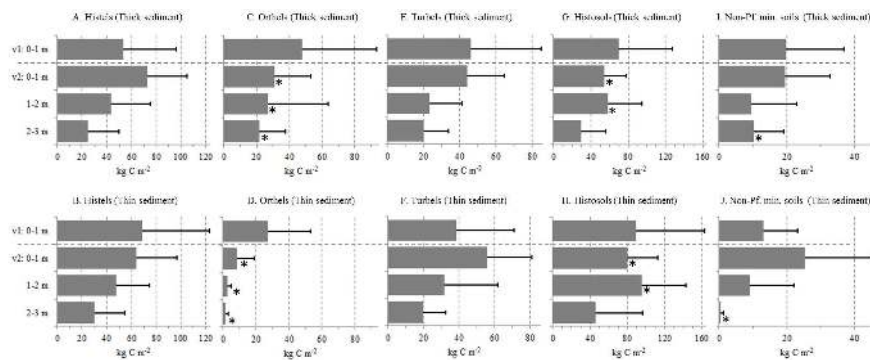


Fig. 2. Mean SOC storage (kg C m^{-2} , with error bars showing StD), subdivided by physiographic regions, for different soil upscaling classes calculated using pedon datasets v1 and v2. Different panels (A) to (J) show estimates for the 0–1 m (pedon datasets v1 and v2), 1–2 m and 2–3 m (pedon dataset 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, $p < 0.05$).

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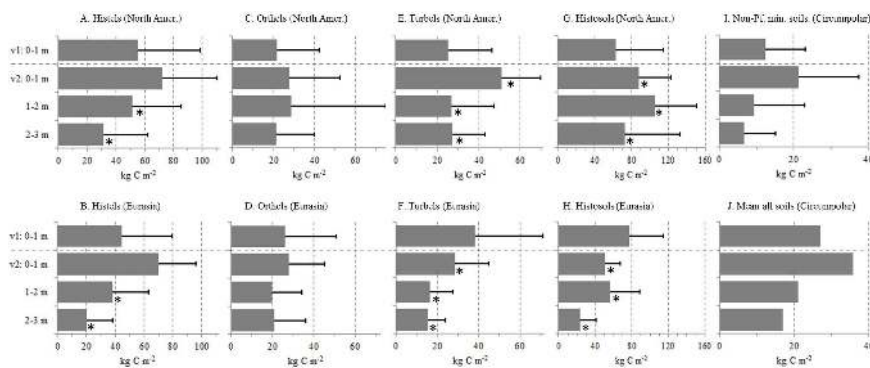


Fig. 3. Mean SOC storage (kg C m^{-2} , with error bars showing StD), subdivided by continents, for different soil upscaling classes calculated using pedon datasets v1 and v2. Different panels (A) to (H) show estimates for the 0–1 m (pedon datasets v1 and v2), 1–2 m and 2–3 m (pedon dataset v2) depth 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 NCSDv2 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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1 **Online supplemental material for:**

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

5 **Hugelius¹, Strauss², Zubrzycki³, Harden⁴, Schuur⁵, Ping⁶, Schirrmeister²,**
6 **Grosse², Michaelson⁶, Koven⁷, O'Donnell⁸, Elberling⁹, Mishra¹⁰, Camill¹¹, Yu¹²,**
7 **Palmtag¹ and Kuhry¹.**

8

9 Submitted to Biogeoscience

10

11 **1 Methods**

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

15 **1.1 Calculating 0–3 m SOC stocks**

16 Calculation of SOC stocks based on thematic soil maps is done in three steps (Hugelius,
17 2012). First, the SOC storage (area-normalized SOC given in kg C m^{-2}) for individual pedons
18 (a pedon is a described/classified and sampled three-dimensional body of soil) is calculated to
19 the selected reference depths. Second, the pedon data is grouped into suitable thematic
20 upscaling classes and mean SOC storage (kg C m^{-2}) for each class and reference depth is
21 calculated. Finally, the mean SOC storage (kg C m^{-2}) of each class is multiplied with
22 estimates of the areal coverage of thematic upscaling classes to calculate absolute SOC stocks
23 (kg C) for different classes and reference depths.

24 For this study, SOC stocks were estimated separately for the 0–0.3 m, 0–1 m, 1–2 m and 2–3
25 m depth ranges (measured from the top of the genetic O-soil horizon, excluding litter and the
26 living capitula of mosses) using the NCSCDv2. The NCSCDv2 is a polygon-based digital
27 database adapted for use in Geographic Information Systems (GIS) which has been compiled
28 from harmonized regional soil classification maps. Map data on soil coverage has been linked

1 to pedon data with SOC storage (kg C m^{-2}) from the northern permafrost regions to estimate
2 geographically upscaled total SOC stocks (Hugelius et al., 2013b).

3 1.1.1 Regional geographic subdivisions in upscaling

4 The SOC stocks estimates for the 0–0.3 m and 0–1 m depth ranges were calculated separately
5 in each NCSCDv2-region (Alaska, Canada, Contiguous USA, Europe, Greenland, Iceland,
6 Kazakhstan, Mongolia, Russia and Svalbard) following the methodology of Tarnocai et al.
7 (2009).

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

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

22 For the second estimate, pedons and mapped soil areas in the NCPR were separated into areas
23 of thick and thin sedimentary overburden (Fig. 1). The spatial extent of the NCPR is defined
24 following the “Circum-Arctic map of permafrost and ground-ice conditions” (Brown et al.,
25 1997; 2002). The spatial base and first order classification criterion used to create this map
26 were regional physiographic or landscape maps (Heginbottom et al., 1993). Based on these
27 regional maps, numerous published data sources and input from regional experts, the NCPR
28 was subdivided into two broad classes (Heginbottom et al., 1993): (1) “areas of lowlands,
29 highlands and intra- and inter-montane depressions characterized by thick overburden,
30 wherein ground ice is expected to be generally fairly extensive” and (2) “areas of mountains,
31 highlands, and plateaus characterized by thin overburden and exposed bedrock, where

1 generally lesser amounts of ground ice are expected to occur” (thick overburden is defined as
2 >5–10 m).

3 1.1.2 Thematic subdivisions of soil classes in upscaling

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

10 For the 1–2 m and 2–3 m depth ranges, a reduced thematic resolution was used. Stocks were
11 calculated separately for the Turbel, Histel and Orthel suborders of the Gelisol soil order and
12 for the Histosol soils order (organic soils without permafrost). All remaining soil orders were
13 grouped as non-permafrost mineral soils. For the continent based upscaling (separating North
14 America and Eurasia) the non-permafrost mineral soils were merged to the whole NCPR
15 because of a lack of pedon data in the Eurasian region.

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

25 1.1.3 Pedon databases and calculation of SOC content

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

1 SOC storage (kg C m^{-2}) values are based on 1778 individual pedons from around the NCPR
2 (mainly Gelisol and Histosol pedons), that have been complemented with SOC storage (kg C
3 m^{-2}) data from Batjes (1996) where data for non-permafrost soil orders was missing (this
4 pedon dataset is hereafter called pedon dataset v1). More detailed information regarding this
5 pedon dataset, including details regarding which soil orders were supplemented from Batjes
6 (1996), can be found in table S1 of the supplementary online materials. For further details
7 regarding the NCSCD GIS-database and the methods for pedon sampling and calculation of
8 0–0.3 and 0–1 m SOC stocks we refer to Hugelius et al. (2013b).

9 For the deeper soil layers (1–2 m and 2–3 m depth ranges) a newly compiled pedon database
10 which has been integrated into the NCSCDv2 was used (Fig. 1; Table 1), from this pedon
11 compilation we included 518 pedons that extend down to 2 m and 351 pedons that extend
12 down to 3 m (this pedon dataset is hereafter called pedon dataset v2). Table 1 summarizes the
13 number of individual pedons available from different geographical regions and areas of
14 thick/thin sedimentary overburden. More detailed information regarding this pedon dataset
15 can be found in table S1 of the supplementary online materials. Pedon dataset v2 includes a
16 large number of pedons that were gap-filled using extrapolated and/or estimated values of
17 bulk density and/or percentage organic carbon content (OC%) (Hugelius et al., 2013a). This
18 applies particularly to organic soils (Histels and Histosols) where the database also includes
19 all available pedons with O-horizons ≥ 40 cm, but that lacked full deep characterization. In
20 these cases, to estimate SOC storage in the underlying mineral subsoil, data from mineral soil
21 genetic C-horizons (i.e. bulk density and OC%) were extrapolated to the full 3 m baseline
22 depth (or default values from other similar sites were used). These extensive extrapolations
23 are used to avoid a sampling bias towards deep peat deposits in the database, which would
24 lead to significant overestimation of deep (>1 m) SOC stocks in organic soils. For full data-
25 access and further details regarding the compilation, gap-filling procedures etc. for pedon
26 dataset v2 we refer to Hugelius et al (2013a).

27 Because different pedon datasets were used to calculate 0–1 m SOC stocks (pedon dataset v1)
28 and 1–3 m SOC stocks (pedon dataset v2), there was a concern that these two dataset may not
29 accurately reflect the same statistical populations (Hugelius, 2012). Therefore, the
30 circumpolar mean 0–1 m SOC storage (kg C m^{-2}) between the two databases was compared
31 using Student's t-test (test from parameters, software PAST v2.17b; Hammer et al. 2001).
32 These tests were performed at the reduced thematic resolution used to calculate deeper SOC

1 stocks. Because the individual pedon observations and coordinates are no longer available for
2 pedon dataset v1, the tests could not be done separately for North America / Eurasia or areas
3 of thick / thin sedimentary overburden (mean, standard deviation and n values of pedon
4 dataset v1 for the separate regions are not known). For each soil upscaling class (reduced
5 thematic resolution), SOC storage (kg C m^{-2}) in the individual depth ranges (0–1 m, 1–2 m
6 and 2–3 m) were also compared across regions (North America vs. Eurasia) and deposit-
7 thickness classes (thick sediments vs. thin sediments) using Student's t-test.

8 **1.2 Calculating deltaic SOC stocks**

9 The approach used to estimate deltaic SOC stocks in this study builds on that of Tarnocai et
10 al. (2009) who used data on the mean depth of alluvium, mean delta lake coverage/depth and
11 mean alluvium SOC storage (kg C m^{-3}) from the Mackenzie River Delta (Canada) combined
12 with data on the spatial coverage of seven large arctic deltas. For the calculation presented
13 here we combine the data used by Tarnocai et al. (2009) with updated information (from
14 scientific literature and databases) on the areal extent of deltas, mean depth of alluvium, delta
15 lake coverage, permafrost extent and segregated ice content in deltaic deposits. The total
16 volume of alluvium for each delta is calculated from the mapped sub-aerial deltas extent and
17 the mean depth of alluvial deposits, subtracting the volume that is estimated to be occupied by
18 massive ice and water bodies. To avoid double counting, the top 3 m of soil as well as known
19 Yedoma deposits located in the Lena Delta are removed from the calculation. When the total
20 volume of alluvium is calculated, the total SOC pool of each delta is estimated using field
21 data of mean alluvium SOC storage (kg C m^{-3}). In all cases, mean values from other deltas
22 were used when there was no direct data for any specific variable in a delta.

23 Walker (1998) provides a baseline estimate of the sub-aerial spatial extent of major Arctic
24 river deltas. We selected this reference for our estimate of delta spatial extent, and included
25 those deltas that are located within the NCPR. Because of the distinct geological histories and
26 general characteristics of the main terraces of the Lena River Delta (Russia) we divided this
27 delta into three terraces and the recent floodplain based on previous research (Grigoriev,
28 1993; Schwamborn et al., 2002; Zubrzycki et al., 2013). Estimates of the fraction of delta
29 surfaces covered by water bodies were available for the Mackenzie River Delta (Smith, 2011)
30 and the Lena River Delta (Morgenstern et al., 2008; 2011).

1 Estimated permafrost extent and massive ice-content in deltaic deposits were extracted from
2 the Circum-Arctic map of permafrost and ground-ice conditions (Brown et al., 2002).
3 Because this product maps massive ice occurrence in the upper 10–20 m of sediment, the
4 mapped massive ice is assumed to extend through the upper 15 m of alluvium (we assume
5 zero massive ice-content below this depth). Schwamborn et al. (2002) show that a talik ca. 95
6 m deep is developed underneath Lake Nikolay on Arga Island (Lena River Delta). Also, Burn
7 (2002) found that most lakes in the Mackenzie River Delta that exceed critical areal-
8 thresholds (18%–27% of all delta lakes) have taliks that extend through the permafrost while
9 littoral margins under shallow water generally have permafrost in the upper few meters.
10 Because of this evidence of taliks below deltaic water-bodies, unfrozen alluvium is assumed
11 to occur primarily under water bodies for the purposes of our calculations.

12 Tarnocai et al. (2009) used a 5 m mean depth of delta water-bodies to calculate the volume of
13 water. Boike et al. (2013) report that depths of polygonal ponds on Samoylov Island (Lena
14 Delta, Russia) range from a few cm up to 1.3 m while inventoried thermokarst lakes are up to
15 6.1 m deep. In the 2nd terrace of the Lena River Delta, lakes reach depths of up to 10–30 m,
16 but large lake expanses are typically <2 m deep (Schwamborn et al., 2002). Field
17 measurements based on ground penetrating radar in the Middle Channel of the Mackenzie
18 River Delta show a maximum depth of ca. 5 m at one location (Stevens et al., 2009). Burn
19 (2002) reports maximum depths from twelve inventoried lakes on Richards Island
20 (Mackenzie River Delta) ranging from 2.1–13.1 m. Water depths in delta water bodies are
21 highly variable and expected to range outside of the values reported above. Because no
22 comprehensive summative data regarding the mean depth of water bodies on delta surfaces is
23 available we also use a mean depth of 5 m for this study.

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

1 **1.3 Calculating Yedoma region permafrost SOC stocks**

2 For the purpose of these calculations, the Yedoma region is subdivided into areas of intact
3 Yedoma deposits (late Pleistocene ice- and organic-rich silty sediments) and permafrost
4 deposits formed in thaw-lake basins (generalized as thermokarst deposits). Areas of unfrozen
5 sediment underlying water bodies and areas covered by deltaic or fluvial sediments were
6 excluded. Twenty-two Yedoma and 10 thermokarst deposit profiles were studied and sampled
7 from river or coastal bluffs exposed by rapid thaw and erosion (Strauss et al., 2013). Total
8 SOC stocks in intact Yedoma and perennially frozen thermokarst deposits for depths >3 m are
9 calculated based on individual observations of: deposit thickness (n=20 and 8, respectively),
10 organic C (weight %, n=682 and 219), bulk density (n=428 and 117), and wedge-ice (volume
11 %, n=10 and 6). For details regarding calculations of the spatial extent of different sediments,
12 data collection and spatial distribution of field observations we refer to Strauss et al. (2013).
13 Because of high inherent (spatial) heterogeneity and non-normal distributed input parameters,
14 the SOC stock calculations are based on bootstrapping techniques using resampled (10,000
15 times) observed values (following methodology of Strauss et al. 2013). After bootstrapping
16 the populations of observations, the total mean pool size estimate was derived from these
17 10,000 bootstrap samples afterward. Because organic C % and bulk density of individual
18 sediment samples are auto-correlated, paired values were used in the resampling process.

19 **1.4 Estimating SOC stock uncertainties**

20 Spatial upscaling using mean values of classes from thematic maps, such as soil maps, builds
21 on the premise that an empirical connection between map classes and the investigated variable
22 can be established through point sampling (Hugelius, 2012). Sources of upscaling-uncertainty
23 in such thematic mean upscaling can be divided into (i) database errors which are
24 uncertainties caused by insufficient field-data representation to describe natural soil
25 variability within an upscaling class and (ii) spatial errors which are uncertainties caused by
26 areal misrepresentation of classes in the upscaling map (Hugelius, 2012). The former can be
27 estimated based on the standard error (reflects variance and number of independent replicates)
28 and the relative contribution towards the total stock of each upscaling class; however, this
29 procedure assumes that the available sample accurately reflects the natural variability within a
30 class. The latter can be assessed if dedicated, comprehensive ground truth datasets to assess
31 map accuracy are available, which is not the case in this study. All uncertainty-estimates

1 assume that the spatial extent of different soil orders, deltas and the Yedoma region within the
2 NCPR are correctly mapped.

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

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

$$9 \quad CI = t \times \sqrt{(\sum (a_i^2 \times StD_i^2) / n_i)} \quad (1)$$

11
12 where: t is the upper $\alpha/2$ of a normal distribution ($t \approx 1.96$ for a 95% CI and $t \approx 2.58$ for a 99%
13 CI), a_i = percentage of the total area/volume for class i , StD_i = standard deviation of the class i ,
14 n_i = number of replicates in class i . For the estimates of near surface soils (0–0.3 m and 0–1
15 m), the calculation was done for the whole NCPR, using mean SOC stocks calculated from
16 the NCSCDv2 and values of StD (translated to the NCSCDv2 means by using the coefficient
17 of variation) and n from Tarnocai et al. (2009) and Batjes (1996). All data used to calculate
18 the different CI ranges are summarized in table S1 of the supplementary online materials.

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

25 1.4.2 Uncertainties of SOC estimates in Yedoma region deposits

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

1 84th percentiles of bootstrapped observations (following Strauss et al., 2013). This uncertainty
2 mirrors the data uncertainty, not only the uncertainty of the mean estimator. To fully estimate
3 the estimator's (observation-based mean) uncertainty, several independent bootstrapping runs,
4 with mean calculation in each case, would be necessary. On the one hand, because single
5 value estimates reduces the variability, a smaller uncertainty range would be inferred with this
6 approach. But on the other hand, the described and applied conservative uncertainty approach,
7 using a single bootstrapping run, is closer to the natural inherent heterogeneity of the dataset.
8 Computations were performed using the open source software R (boot package).

9 1.4.3 Combining confidence intervals/uncertainty estimates

10 Combined propagated uncertainty ranges when summing up the different depth ranges (CI_{0-1}
11 $m+CI_{1-2}$ m etc.) or different components (CI_{0-3} m + CI_{delta} etc.) of the total NCPR SOC stocks
12 were calculated in two ways:

- 13 1. ($_{add}CI$) by addition of the relative CI ranges of different components (CI_x+CI_y etc.).
- 14 2. ($_{cov}CI$) by using a formula for additive error propagation of covarying variables
15 (Roddick, 1987):

16

$$17 \text{cov}CI = \sqrt{(CI_x^2 \times CI_y^2 + 2\rho_{xy}CI_xCI_y)} \quad (2)$$

18

19 Where ρ_{xy} is the correlation coefficient of variables x and y. The summative calculations
20 were done in several steps, first the correlation coefficient between 0–1 m and 1–2 m SOC
21 storage (kg C m^{-2}) in pedon spreadsheet v2 ($\rho=0.58$, $p<0.05$) was used to calculate $covCI$ for
22 the 0–2 m SOC stocks. In a second step the correlation coefficient between 0–2 m and 2–3 m
23 SOC storage (kg C m^{-2}) in pedon spreadsheet v2 ($\rho=0.41$, $p<0.05$) was used to calculate
24 $covCI$ for the 0–3 m SOC stocks. For the purpose of these calculations SOC storage in the 0–
25 3 m depth range is assumed to be uncorrelated to Yedoma region and deltaic SOC storage.

26

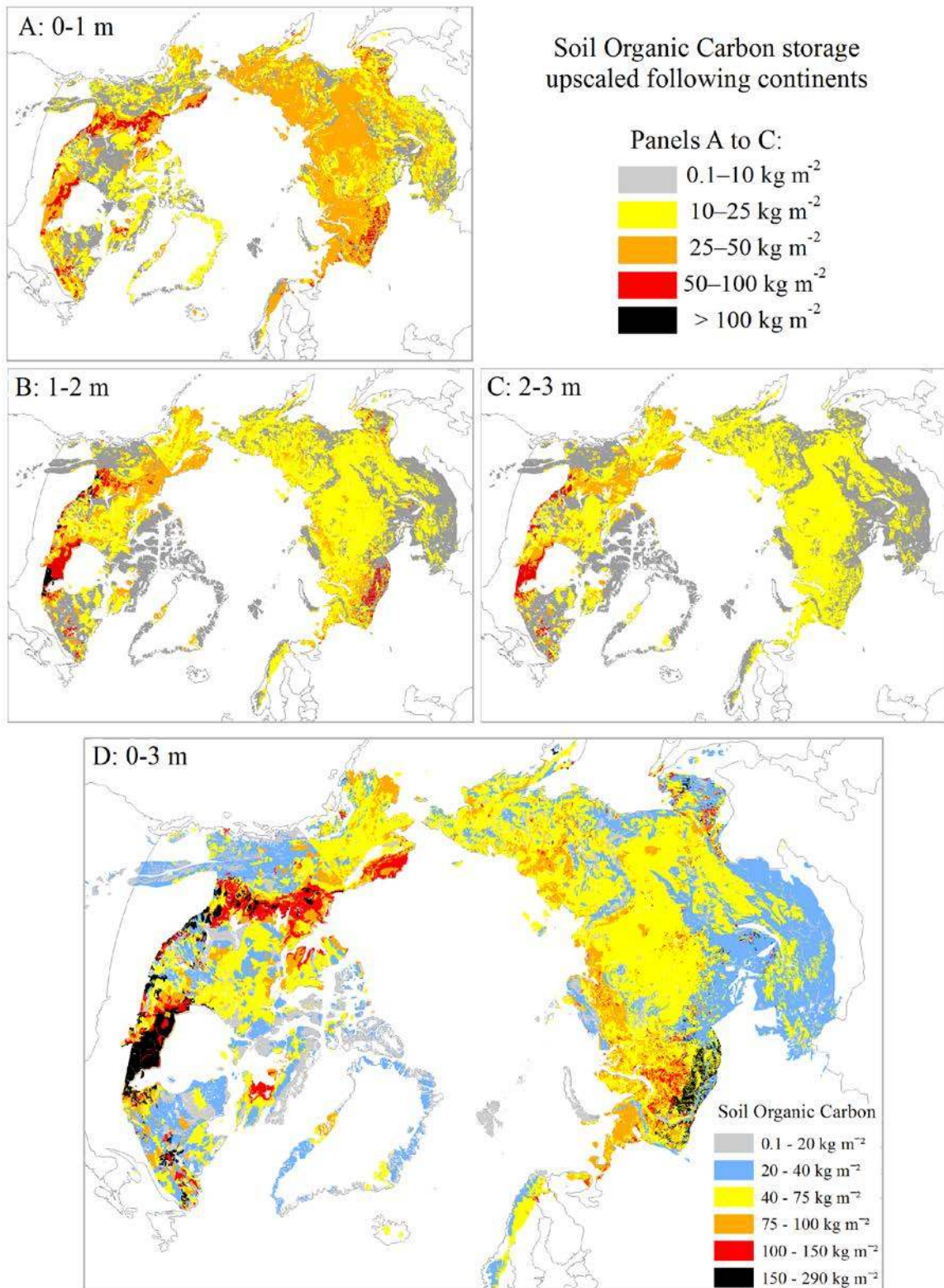
27

28

29

1

2 2 Results



3

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

5

6 **References**

- 7 Batjes, N.H.: Total carbon and nitrogen in the soils of the world. *European Journal of Soil*
8 *Science* 47, 151-163, 1996
- 9 Brown, J. Ferrians, O.J. Jr., Heginbottom, J.A. and Melnikov, E.S.: Circum-Arctic map of
10 permafrost and ground-ice conditions, 1:10 000 000, Map CP-45, United States Geological
11 Survey, International Permafrost Association, 1997
- 12 Brown, J. Ferrians, O.J. Jr., Heginbottom, J.A. and Melnikov, E.S.: Circum-Arctic Map of
13 Permafrost and Ground-Ice Conditions, version 2, Boulder, Colorado USA, National Snow
14 and Ice Data Center, 2002
- 15 Boike, J., Kattenstroth, B., Abramova, K., Bornemann, N., Chetverova, A., Fedorova, I.,
16 Fröb, K., Grigoriev, M., Grüber, M., Kutzbach, L., Langer, M., Minke, M., Muster, S., Piel,
17 K., Pfeiffer, E.-M., Stoof, G., Westermann, S., Wischnewski, K., Wille, C., and Hubberten,
18 H.-W.: Baseline characteristics of climate, permafrost and land cover from a new permafrost
19 observatory in the Lena River Delta, Siberia (1998–2011), *Biogeosciences*, 10, 2105–2128,
20 doi:10.5194/bg-10-2105-2013, 2013.
- 21 Burn C.R.: Tundra lakes and permafrost, Richards Island, western Arctic coast, Canada.
22 *Canadian Journal of Earth Sciences* 39, 1281–1298, doi: 10.1139/E02-035, 2002
- 23 Hammer, Ø., Harper D. A. T. and Ryan P. D.: PAST: Paleontological statistics software
24 package for education and data analysis, *Palaeontol. Electron.*, 4(1), 1–10, 2001
- 25 Heginbottom J.A., Brown J., Melnikov E.S. and Ferrians O.J.: Circumarctic map of
26 permafrost and ground ice conditions, Sixth International Conference, Beijing, Proceedings.
27 Wushan, Guangzhou, China, South China University Press, volume 2, 1132-1136, 1993
- 28 Hugelius G.: Spatial upscaling using thematic maps: an analysis of uncertainties in permafrost
29 soil carbon estimates, *Global Biogeochemical Cycles*, doi:10.1029/2011GB004154, 2012

- 1 Hugelius G., Bockheim J.G., Camill P., Elberling B., Grosse G., Harden J.W., Johnson K.,
2 Jorgenson T., Koven C.D., Kuhry P., Michaelson G., Mishra U., Palmtag J., Ping C.-L.,
3 O'Donnell J., Schirrmeister L., Schuur E.A.G., Sheng Y., Smith L.C., Strauss J. and Yu Z.: A
4 new data set for estimating organic carbon storage to 3 m depth in soils of the northern
5 circumpolar permafrost region, *Earth System Science Data*, 5, 393–402, doi:10.5194/essd-5-
6 393-2013, 2013b
- 7 Hugelius, G., Tarnocai, C., Broll, G., Canadell, J. G., Kuhry, P., and Swanson, D.: The
8 Northern Circumpolar Soil Carbon Database: spatially distributed datasets of soil coverage
9 and soil carbon storage in the northern permafrost regions, *Earth System Science Data*, 5, 3-
10 13. doi:10.5194/essd-5-3-2013, 2013a
- 11 Stevens C.W., Moorman B.J., Solomon S.M. and Hugenholz C.H.: Mapping subsurface
12 conditions within the near-shore zone of an Arctic delta using ground penetrating radar, *Cold*
13 *Regions Science and Technology*, 56, 30-38, doi:10.1016/j.coldregions.2008.09.005, 2009
- 14 Strauss, J., Schirrmeister, L., Grosse, G., Wetterich, S., Ulrich, M., Herzsuh, U., and
15 Hubberten, H.-W.: The deep permafrost carbon pool of the Yedoma region in Siberia and
16 Alaska, *Geophys. Res. Lett.*, 40, 6165–6170, doi:10.1002/2013GL058088, 2013
- 17 Tarnocai, C., Canadell, J., Mazhitova, G., Schuur, E.A.G., Kuhry, P. and Zimov, S.: Soil
18 organic carbon stocks in the northern circumpolar permafrost region. *Global Biogeochem.*
19 *Cycles*, 23, GB2023, doi:10.1029/2008GB003327, 2009
- 20 Thompson, S. K.: *Sampling*, 343 pp., John Wiley, New York, 1992
- 21 Walker, D. A., Reynolds, M. K., Daniels, F. J. A., Einarsson, E., Elvebakk, A., William, W.
22 A., Katenin, A. E. Kholod, S. S., Markon, C. J., Evgeny, S., Moskalenko, N. G., S.Talbot, S.,
23 and Yurtsev, B. A.: The circumpolar Arctic vegetation map. *Journal of Vegetation Science*,
24 16(3), 267–282, 2005.
- 25 Walker, H. J.: Arctic deltas, *J. Coast. Res.*, 14, 718–738, 1998.