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   **Hugelius[1], Strauss[2], Zubrzycki[3], Harden[4], Schuur[5], Ping[6], Schirrmeister[2],**

6   **Grosse[2], Michaelson[6], Koven[7], O'Donnell[8], Elberling[9], Mishra[10], Camill[11], Yu[12],**

7   **Palmtag[1] and Kuhry[1].**

8

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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.

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).

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).

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).

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

3

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

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

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

10 $$CI = t \times \sqrt{\left(\sum\left(\left(a_i^2 \times StD_i^2\right) / n_i\right)\right)} \qquad \qquad (1)$$

11

12 where: t is the upper $\alpha/2$ of a normal distribution (t≈1.96 for a 95% CI and t≈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.

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

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 ($CI_{0-1 \text{ m}}$ + $CI_{1-2 \text{ m}}$ etc.) or different components ($CI_{0-3 \text{ m}}$ + CI_{delta} etc.) of the total NCPR SOC stocks were calculated in two ways:

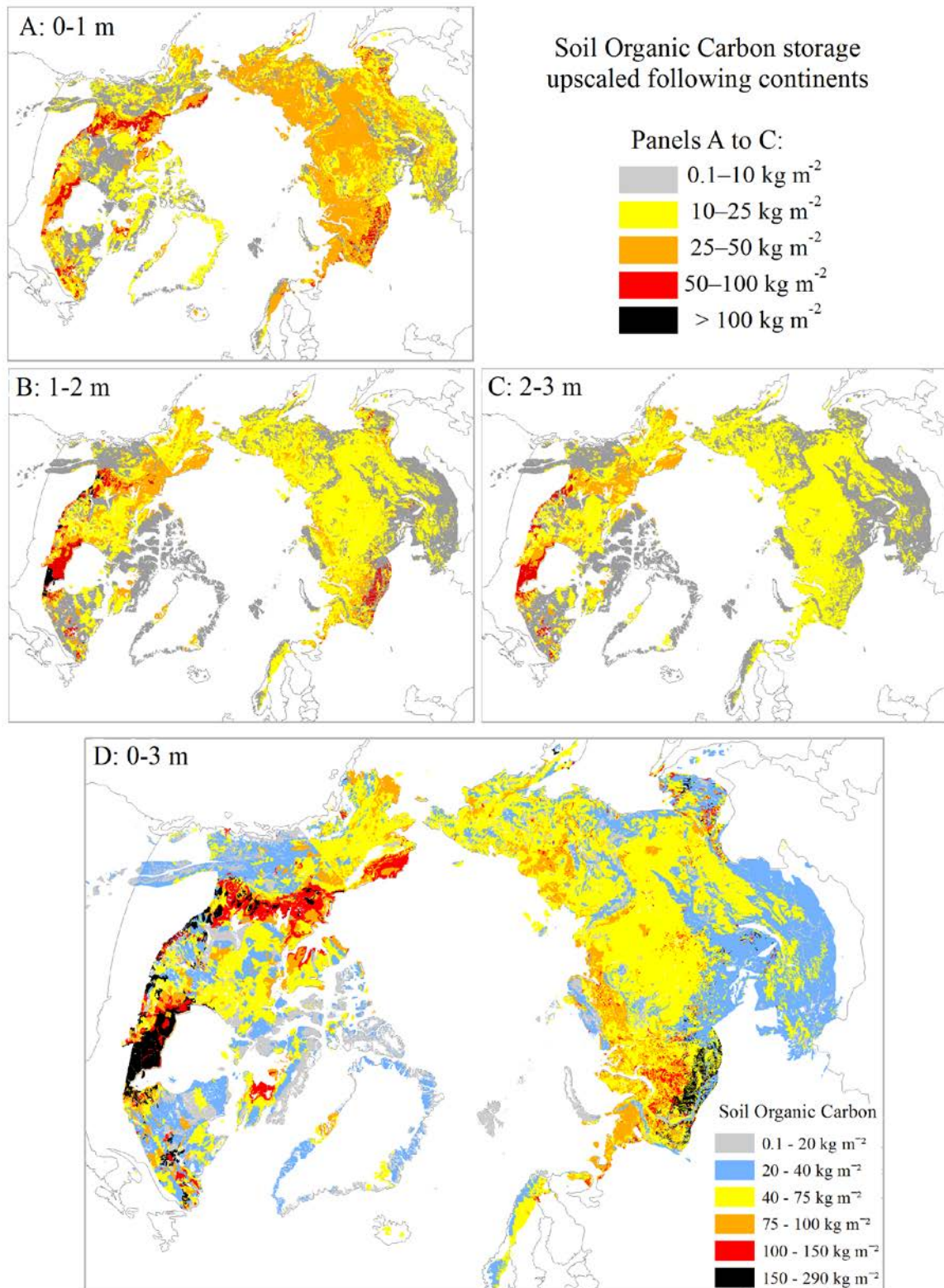1.   ($_{add}CI$) by addition of the relative CI ranges of different components (CI_x+CI_y etc.).

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

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

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 (ρ=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 (ρ=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.

1

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}

3

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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