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A new data set for estimating organic carbon storage to 3 m depth in soils of the northern circumpolar permafrost region

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Abstract. High-latitude terrestrial ecosystems are key components in the global carbon cycle. The Northern Circumpolar Soil Carbon Database (NCSCD) was developed to quantify stocks of soil organic carbon (SOC) in the northern circumpolar permafrost region (a total area of 18.7×10^6 km^2). The NCSCD is a geographical information system (GIS) data set that has been constructed using harmonized regional soil classification maps together with pedon data from the northern permafrost region. Previously, the NCSCD has been used to calculate SOC storage to the reference depths 0–30 cm and 0–100 cm (based on 1778 pedons). It has been shown that soils of the northern circumpolar permafrost region also contain significant quantities of SOC in the 100–300 cm depth range, but there has been no circumpolar compilation of pedon data to quantify this deeper SOC pool and there are no spatially distributed estimates of SOC storage below 100 cm depth in this region. Here we describe the synthesis of an updated pedon data set for SOC storage (kg C m^{-2}) in deep soils of the northern circumpolar permafrost regions, with separate data sets for the 100–200 cm (524 pedons) and 200–300 cm (356 pedons) depth ranges. These pedons have been grouped into the North American and Eurasian sectors and the mean SOC storage for different soil taxa (subdivided into Gelisols including the sub-orders Histels, Turbels, Orthels, permafrost-free Histosols, and permafrost-free mineral soil orders) has been added to the updated NCSCDv2. The updated version of the data set is freely available online in different file formats and spatial resolutions that enable spatially explicit applications in GIS mapping and terrestrial ecosystem models. While this newly compiled data set adds to our knowledge of SOC in the 100–300 cm depth range, it also reveals that large uncertainties remain. Identified data gaps include spatial coverage of deep (> 100 cm) pedons in many regions as well as the spatial extent of areas with thin soils overlying bedrock and the quantity and distribution of massive ground ice. An open access data-portal for the pedon data set and the GIS-data sets is available online at http://bolin.su.se/data/ncscd/. The NCSCDv2 data set has a digital object identifier (doi:10.5879/ECDS/00000002).

1 Introduction

High latitude terrestrial ecosystems are considered key components in the global carbon (C) cycle (McGuire et al., 2009). In these regions, low temperatures and high soil-water contents reduce decomposition rates (Davidson and Janssens, 2006) and fire combustion losses (Harden et al., 2000). Important processes of soil organic C (SOC) accumulation include peat formation, sustained accumulation of syngenetic sedimentary deposits and burial of SOC through cryoturbation (Ping et al., 1998; Tarnocai and Stolbovoy, 2006; Schirrmeister et al., 2011).Together this has resulted in an accumulation of large stocks of SOC in permafrost mineral soils, organic soils, deltaic deposits and ice-rich, late Pleistocene silty deposits (Yedoma) (Schuur et al., 2008). If widespread permafrost thaw occurs, SOC that was previously protected in permafrost may be mineralized leading to increased greenhouse gas fluxes to the atmosphere (Grosse et al., 2011; Schuur et al., 2013).

Using the Northern Circumpolar Soil Carbon Database (NCSCD; see Hugelius et al., 2013 for a full technical description of the data set), Tarnocai et al. (2009) estimated the SOC pool to be 191 Pg (1 Pg = 10^{12} kg) for topsoil (0–30 cm depth) and 496 Pg for the upper 100 cm of soil in the northern circumpolar permafrost region (a total area of 18.7×10^6 km^2 as estimated by Brown et al., 1997). The SOC pool to 300 cm soil depth was estimated to be 1024 Pg (Tarnocai et al., 2009). This estimate of SOC to 300 cm depth was based on limited field data of 46 pedons, and was not included in the first version of the spatially distributed NCSCD. The estimated SOC pool in deeper (> 300 cm) Yedoma deposits (407 Pg) and deltaic deposits (241 Pg) brings the total estimate to 1672 Pg, of which 1466 Pg is stored in perennially frozen ground (Tarnocai et al., 2009). This is about twice as much C as in the atmosphere (Houghton, 2007).

While it is recognized that the SOC pool stored in permafrost regions is very large and vulnerable to remobilization through permafrost thaw (Elberling et al., 2013), pool estimates are poorly constrained and quantitative error estimates are lacking (Hugelius, 2012). Tarnocai et al. (2009) assigned qualitative levels of confidence for different components of the circumpolar SOC estimate. The deep soil (100–300 cm) estimate was assigned the lowest degree of confidence (low to very low) because of a lack of field data and limited spatial representativeness.

Here we describe the compilation of an updated pedon data set for describing SOC storage (kg C m^{-2}) in deep soils of the northern circumpolar permafrost regions. The new data set provides separate estimates for the 100–200 cm and 200–300 cm depth ranges, and represents a significant increase in the amount of available pedons compared to the previous estimate (increase by factors 11 and 8 for the two depth ranges, respectively). This data set has been integrated with the NCSCD (Hugelius et al., 2013) to enable upscaling and calculation of regional and circumpolar SOC stocks. The updated NCSCDv2 is freely available online in several different file formats and spatial resolutions that enable its applications in geographical information system (GIS) mappings and terrestrial ecosystem models.

2 Data set structure

We used the following two criteria to evaluate georeferenced pedon data for inclusion into the updated data set. (1) Pedon described following a classification system suitable for permafrost affected soils, e.g., US Soil Taxonomy, The Canadian System of Soil Classification or the World Reference Base for soil resources (Soil Survey Staff, 1999; Soil Classification Working Group, 1998; IUSS Working Group WRB, 2007). (2) Data available on percentage organic C (OC %), percentage coarse fragments (> 2 mm diameter) and/or segregated ice content (percentage weight) and dry bulk density (BD) of described soil horizons down to sufficient soil depths (≥ 150 cm, see Sect. 2.1 below).

Data sources include pedons from previously published scientific studies, existing databases and previously unpublished material (all original data sources are provided in the pedon data set spreadsheet). The compiled data set follows the US Soil Taxonomy classification. The data set is subdivided into the following classes: the three sub-orders of the Gelisol soil order (Histels, Turbels and Orthels) as separate classes, the Histosol soil order as a separate class and, lastly, all remaining soil orders (non-permafrost mineral soil orders) grouped as one class. Peat cores from the West Siberian Lowland (Smith et al., 2012, supplementary online material, $n = 102$) that are located within the northern circumpolar permafrost region were also used in the study. While these sites lack a pedon description, in this study they are classified as Histosols if there is a surface O-horizon of > 40 cm in depth and they are described as non-permafrost or alternatively they are classified as Histels if there is a > 40 cm surface O-horizon and the presence of permafrost is confirmed from measured thaw depths included within this data set. For a subset of cores with no information on the absence or presence of permafrost ($n = 11$, applies to pre-existing Russian peat cores collected from literature by Smith et al., 2012), only those sites that are located within the continuous permafrost zone are included (classified as Histels).

2.1 Soil sampling, analyses and calculations

In general, deep soil cores (> 100 cm depth) were collected using motorized coring equipment or through manual soil coring. In some cases pedons were sampled from natural exposures (e.g., along river banks, coastal bluffs or thermal erosion fronts) that were cleaned to expose fresh soil material prior to sampling. For detailed descriptions of soil sampling methodology, laboratory analyses and calculation of soil horizon SOC storage, we refer to Hugelius et al. (2013).

For the West Siberian Lowland peat cores ($n = 102$), only loss on ignition (LOI) was available to estimate OC %. To translate LOI % into OC % a 2nd order polynomial regression model (OC % = $(-0.0013 \times \text{LOI}\,\%^2) + (0.637 \times \text{LOI}\,\%)$) with an $R^2 = 0.79$ was created based on 101 peat samples from similar environments and peat deposits in the Pechora River basin where both LOI and OC % was measured on the same homogenized samples (Hugelius et al., 2011). For mineral soil samples from the same data set, the regression for LOI % to OC % conversion described by Hugelius et al. (2011) was used ($n = 171$, $R^2 = 0.98$; OC % = $(-0.00005 \times \text{LOI}\,\%^3) + (0.0059 \times \text{LOI}\,\%^2) + (0.362 \times \text{LOI}\,\%)$).

In many places the pedon data set was incomplete and data-gap filling (pedo-transfer functions), extrapolation or estimation was needed to complete calculations. The details of these procedures are described below. All pedons where such procedures have been used are flagged in the pedon data set so that data users may easily identify them.

2.1.1 Gap filling with pedo-transfer functions

In some pedons ($n = 25$, all from silty sediments) a subset of the sampled soil horizons lacked data for BD which was gap filled using a power-based regression model that approximates BD from OC % from Muhs et al. (2003). The regression model (BD = $1.4593\,(-0.133 \times \text{OC}\,\%)$) is based on 282 loess samples and has an $R^2 = 0.73$. A correction for volumetric ice content was used in permafrost soil horizons, based on measured ice content data.

2.1.2 Extrapolation and estimates based on default values

In pedons where field data were not available to full depths of 200 or 300 cm, the lower-most available values for BD and OC % in that pedon were extrapolated to the full depth if field data were available for depths within 50 cm of the full depth ($n = 41$ (8 %) and $n = 37$ (10 %) for 200 and 300 cm depths, respectively). Such extrapolations were limited to C soil genetic horizons or deep, homogenous, Quaternary deposits (loess or deltaic deposits) where it was likely a similar soil material extended beyond the final sampling depth.

To avoid overestimation of deep SOC storage to depths of 200 or 300 cm, areas with unconsolidated deposits shallower than 200 or 300 cm should also be accounted for. The compiled data set includes all available pedons which describe the occurence of bedrock or massive ice within the 0–300 cm depth range. Massive ice and bedrock is assumed to contain no organic C. It should be noted that even though these shallower soil pedons were incorporated into the estimates, this cannot remove any original bias that may have been caused by deep soil sampling occurring in targeted sites with deeper soils as compared to an unbiased landscape average.

To avoid a similar bias for deep organic soils in the data set, the data set also includes organic soil pedons (Histosols and Histels) with relatively shallow (≥ 40 cm) O-horizons but that lacked full deep characterization to 200 or 300 cm ($n = 110$). To estimate SOC storage in the underlying mineral subsoil of these pedons, data from mineral soil genetic C-horizons were extrapolated to the full 300 cm baseline depth. In those cases where the underlying mineral soil was not sampled, the default values BD = 1.04 ± 0.53 g cm^{-3} and SOC % = 3.29 ± 2.98 % were used for extrapolation from the upper 30 cm of mineral soil beneath peat deposits (mean ± one standard deviation value calculated from mineral soil horizons within 30 cm depth below peat deposits in organic soils, $n = 98$) and below that a C-horizon default SOC density of 9.6 kg C m^{-3} was used (following Hugelius and Kuhry, 2009).

2.2 Calculating SOC storage for soil taxa in different regions

The compiled pedon data set was used to calculate regionalized mean SOC storage for those soil taxa where data were available to the reference depths: 0–30 cm (topsoil), 0–100 cm, 100–200 cm and 200–300 cm. All calculations were based on the complete gap-filled data set as presented in the pedon data set spreadsheet. As there was insufficient representation of soil taxa for most individual regions of the NCSCD (for discussion of sample sizes in thematic upscaling, see Hugelius, 2012), we grouped the data into the North

Table 1. Summary of number of available pedons with data in the 100–200 cm (the first number) and 200–300 cm (the second number) depth ranges for soil taxa from different regions (regional subdivision following NCSCD). The regions are grouped into the North American and Eurasian sections of the northern circumpolar permafrost region.

Soil types (*n* of pedons at 100–200 cm/200–300 cm)								
Soil order	Gelisol			Histosol	Alfisol	Entisol	Inceptisol	Spodosol
Soil sub-order	Histel	Turbel	Orthel					
North America[1]								
Alaska	31/31	53/8	29/8	6/6	–	14/1	45/8	8/–
Canada	57/56	8/5	9/5	10/10	5/5	3/1	10/5	–
Greenland	1/1	1/–	6/1	–	–	–	–	–
Eurasia[2]								
Scandinavia/Svalbard	1/1	–	2/2	–	–	–	–	–
Russia	95/94	24/14	27/21	66/66	–	2/2	9/7	4/1
Total	186/184	90/29	73/37	82/82	5/5	19/4	64/20	12/1

[1] There are no pedons in the NCSCD region Contiguous USA.
[2] There are no available pedons in the NCSCD regions Mongolia, Iceland or Kazakhstan.

American (including Greenland) and Eurasian sector. Table 1 provides a summary of the number of available pedons in upscaling soil classes from different geographic regions. For a methodological description of the procedure for calculating pedon SOC storage, see Hugelius et al. (2013). The mean SOC storage (kg C m^{-2}) values to the four reference depths were calculated for different soil orders and soil sub-orders. The full data set including geographic coordinates, soil classification following US Soil Taxonomy, SOC storage (kg C m^{-2}) to the four reference depths, original source/citation for the data and additional site information (site vegetation and/or geomorphological description and thaw depth at the time of sampling) is available online in spreadsheet format. The different soil taxa where tested for class independence by comparing 0–200 or 0–300 cm SOC storage (kg C m^{-2}) in between upscaling classes using Student's *t* test in the statistical software PAST (Hammer et al., 2001). See Hugelius (2012) for a comprehensive discussion of class subdivision in upscaling. The SOC storage calculated from peat cores from the West Siberian Lowlands were also compared against other organic soils from the Russian sector included in the current data set.

2.3 Incorporating data into the updated NCSCDv2

All GIS-analyses have been performed using the software package ArcGIS Desktop, release 10.0 (Environmental Systems Research Institute, Redlands CA, USA). The polygon data set of the NCSCD accounts for percentage coverage and polygon mean SOC storage (kg C m^{-2}) and total SOC stocks (kg C) in the 0–30 cm and 0–100 depth ranges of all soil orders as well as the three sub-orders of the Gelisol soil order (Histels, Turbels and Orthels) in soil taxonomy. The new pedon spreadsheet data set corresponds to this thematic resolution but for spatial upscaling and calculation of polygon SOC a reduced geographic and thematic resolution is used (see Results/Discussion). The version of the NCSCD that includes these new 100–200 and 200–300 cm SOC data is called NCSCDv2.

The SOC storage data were included into the NCSCDv2 by adding new columns containing 100–200 and 200–300 cm mean SOC storage (kg C m^{-2}) to the regional shape-files and calculating total 100–200 and 200–300 cm SOC stocks (kg C) for the separate regions. The regional data sets were merged to form a combined circumpolar polygon shapefile. The new regional 100–200 and 200–300 cm SOC storage (kg C m^{-2}) data was converted to gridded formats. See Hugelius et al. (2013) for a technical description of merging and rasterization of geospatial polygon data. Tables 2 and 3 describe the additional variables that were added to the updated NCSCDv2 (information complementary to tables 2 and 3 in Hugelius et al., 2013).

The NCSCDv2 is also updated by recalculation of 0–30 and 0–100 cm SOC stocks for the Entisol, Spodosol, Histosol, Mollisol and Orthel soil classes for polygons in Alaska, where data for some polygons was found to be missing in the earlier NCSCD version.

3 Results and discussion

This updated pedon data set provides a framework for spatially distributed quantification of SOC at 100–300 cm depths in soils across the circumpolar permafrost region using the NCSCDv2 (Fig. 2). A previous first-order estimate of SOC stocks in this deeper soil component was based on a significantly smaller pedon data set and was not included in the

Table 2. Description of the data added to the polygon attribute tables of NCSCDv2. The table gives a description of the data, the column field name, the precision of numeric fields (Prec), the data format the variable is stored in (Form: F = float numeric field, I = integer numeric field, S = string) and the number of decimal values of float numeric fields (Dec). This table is complementary to Table 2 in Hugelius et al. (2013). This table and the polygon attribute tables of NCSCDv2 uses the abbreviations SOC content (SOCC, $kg\,C\,m^{-2}$) and SOC mass (SOCM, kg C) following Hugelius et al. (2013).

Description	Field name	Prec	Form	Dec
SOCM 100–200 cm depth Histel (kg)	GEHSOCM200	16	F	1
SOCM 100–200 cm depth Turbel (kg)	GETSOCM200	16	F	1
SOCM 100–200 cm depth Orthel (kg)	GEOSOCM200	16	F	1
SOCM 100–200 cm depth non-permafr., mineral soils (kg)	NPMSOCM200	16	F	1
SOCM 100–200 cm depth Histosol (kg)	HISOCM200	16	F	1
SOCM 200–300 cm depth Histel (kg)	GEHSOCM300	16	F	1
SOCM 200–300 cm depth Turbel (kg)	GETSOCM300	16	F	1
SOCM 200–300 cm depth Orthel (kg)	GEOSOCM300	16	F	1
SOCM 200–300 cm depth non-permafr., mineral soils (kg)	NPMSOCM300	16	F	1
SOCM 200–300 cm depth Histosol (kg)	HISOCM300	16	F	1
SOCM 100–200 cm depth of polygon (kg)	SOCM_200	16	F	1
SOCM 200–300 cm depth of polygon (kg)	SOCM_300	16	F	1
SOCC 100–200 cm depth of polygon ($kg\,m^{-2}$)	SOCC_200	8	F	1
SOCC 200–300 cm depth of polygon ($kg\,m^{-2}$)	SOCC_300	8	F	1

Table 3. Description of the NCSCDv2 variables that have been converted to gridded file formats (TIFF-files and NetCDF-files). Each variable is stored in a separate gridded file. This table is complementary to Table 3 in Hugelius et al. (2013). This table and NCSCDv2 files uses the abbreviation SOC content (SOCC, $kg\,C\,m^{-2}$) following Hugelius et al. (2013).

Variable	Description
Coverage Gelisols	Coverage (%) of permafrost affected soils (incl. Turbels, Histels and Orthels)
SOCC 100–200 cm depth	SOCC ($hgC\,m^{-2}$) in the 100–200 cm depth interval
SOCC 200–300 cm depth	SOCC ($hgC\,m^{-2}$) in the 200–300 cm depth interval

NCSCD as a spatially distributed variable (Tarnocai et al., 2009). Harden et al. (2012) combined a larger pedon data set (131 pedons extending to ≥ 150 cm depth and 49 pedons extending to ≥ 250 cm depth) with numbers of total areal coverage of the three Gelisol sub-orders reported in the NCSCD. This data was used to estimate SOCM in the Gelisol soil order, but did not include spatially distributed estimates. In the supplementary information of Harden et al. (2012) more detailed data on depth distribution of C and nitrogen is available, reported on a Gelisol sub-order basis as averages for 5 cm depth increments.

3.1 Data set structure

The database is subdivided into classes which reflect our process understanding of how SOC is incorporated into deep soils. Gelisols and Histosols are affected by specific pedogenic processes that may cause C to be incorporated into the deeper layers of soils. These include cryoturbation (Turbels only), long-term accumulation of peat (Histels and Histosols only) and repeated deposition and stabilization of organic-rich material (alluvium, proluvium, colluvium, lacustrine, marine or wind-blown deposits) in mineral syngenetic permafrost deposits (Ping et al., 1998; Tarnocai and Stolbovoy, 2006; Ping et al., 2011; Schirrmeister et al., 2011; Strauss et al., 2012). For permafrost-free mineral soils the main mechanisms for moving SOC into deeper soil layers are deep plant rooting, leaching of dissolved organic carbon, and burial of organic matter by repeated deposition. The permafrost-free mineral soils in periglacial regions are often poorly developed (Tarnocai et al., 2009). As the vegetation in these regions is relatively shallow-rooted (Kleidon, 2004), it contributes little C to the deeper soil layers. To account for identified important soil forming processes, the three sub-orders of Gelisols are retained as separate classes in the data set and the Histosols are separated from mineral soils without permafrost. Tests of class independence also confirm that the SOC storage ($kg\,C\,m^{-2}$) of these soil taxa are suitably separated for upscaling (t test, $p < 0.05$). Harden et al. (2012) showed that there is a significantly higher SOC density in Gelisol mineral soil horizons impacted by gleying, but this process is not accounted for in this current version of the data set.

3.2 Permafrost-free mineral soils

Of the permafrost-free mineral soil orders, the Alfisols, Entisols, Inceptisols, and Spodosols are represented in the present 100–300 cm pedon data set. The representation of pedons largely corresponds to the geographical range of soil orders. In the NCSCD, the Inceptisols, Spodosols, Entisols, and Alfisols cover 15.8 %, 8.6 %, 4.3 % and 3.6 %, respectively, of the soil area in the northern circumpolar permafrost region. The Mollisols are also significant with 3.5 % coverage, but are not represented in the current data set because of a lack of data. In a regional study of SOC storage in periglacial terrain, Hugelius (2012) found that most permafrost-free mineral soil classes could be amalgamated into one class with very little effect on the overall upscaling results. Analogous tests of the NCSCDv2 show that there is no statistically significant difference in the 0–300 cm SOC storage (kg C m^{-2}) for most of the permafrost-free mineral soil orders (t test, $p > 0.05$). The only exception is that Alfisols store significantly less SOC than all other soil orders. However, the Alfisols are represented by few sites with a very narrow geographical range (5 sites all within a 45 km radius). For upscaling in the NCSCDv2, all permafrost free mineral soil orders were aggregated into one class with circumpolar coverage. This aggregation was done because they have an uneven geographical distribution of pedons (Table 1), they are similar with regards to 0–300 cm SOC stocks and because several permafrost-free mineral soil orders are not represented in the present 100–300 cm data set.

3.3 Shallow soils and massive ground ice

In many parts of the northern circumpolar permafrost region, soils may be absent or unconsolidated deposits do not extend to depths of 300 cm. The NCSCD partly accounts for this by mapping areas of non-soil, including rocklands. In other areas, shallow soils (< 300 cm deep) may overlie bedrock and in some regions there are significant occurrences of massive ground ice (Schirrmeister et al., 2011). In this present data set all available pedons that terminate in bedrock ($n = 8$) or massive ice ($n = 7$) are also included. While we thus assume that these available pedons represent an unbiased and representative sample of circumpolar soils, we recognize that the occurrence of shallow soils or massive ground ice is not adequately accounted for in the current data set. Because pedons are grouped for continental scale areas when upscaling, local or regional differences in deep SOC storage may be poorly represented.

Field studies have shown that massive ground ice accounts for up to 30 % of upper permafrost in Alaskan soils (Kanevskiy et al., 2013) or up to 50–80 % in low land soils in Greenland (Elberling et al., 2010) as well as in Yedoma deposits (Kanevskiy et al., 2013; Schirrmeister et al., 2011). This important issue needs further investigation, including field investigations to quantify ground-ice content and distribution over larger geographical areas.

3.4 Organic soils

In permafrost affected soils, the SOC density is significantly higher in organic horizons than in mineral soil horizons (Harden et al., 2012), and non-permafrost peatlands (Histosols) are dominated by organic horizons with very high SOC density values (Yu, 2012). To accurately estimate SOC stocks of Histosols and Histels, the depth of surface O-horizons is a key variable (Hugelius, 2012). When sampling soils in the field, researchers often strive to reach the bottom of deep organic soils in order to accurately describe the depth distribution and deep SOC storage of these deposits. Many peat cores were also collected for purposes of paleoenvironmental reconstructions, when there is often a specific interest in coring the deepest parts of a peat deposit. Together, these circumstances may cause a bias toward overestimates of organic soil depths. On the other hand, in organic soils with shallower O-horizons researchers are more likely to stop coring well before 200 or 300 cm depth. To avoid a bias towards deep organic soils in the data set, all sites with organic soils were included in this study, even if data from the mineral subsoil was missing. The available data from mineral C-horizons below organic deposits were subsequently extrapolated to full depth (or default values were applied).

There is evidence of widespread, synchronous, early Holocene peat formation in the West Siberian Lowlands (Smith et al., 2004). There was a concern that peat SOC storage in organic soils of this region might differ substantially compared to other organic soils in the Russian permafrost zone where initial peat formation may have occurred less synchronously, over other time periods. In the currently assembled data set, we find no significant difference in 0–300 cm SOC storage (kg C m^{-2}) between Histels from the West Siberian Lowland and Russian Histels outside of the West Siberian Lowland (t test, $p > 0.05$); however, West Siberian Lowland Histosols in the permafrost region have significantly less 0–300 cm SOC storage than Russian Histosols in the permafrost region outside of the West Siberian Lowland (t test, $p < 0.05$). There are no significant differences in reported peat depths or peat OC % between regions (t test, $p > 0.05$). This difference in 0–300 cm SOC storage is mainly due to lower bulk densities reported for Histosols in the West Siberian Lowlands compared to Histosols from other parts of Russia (t test, $p < 0.05$). No separation of the West Siberian Lowland compared to other Russian regions was made in the upscaling.

3.5 Issues of data quality

Data gap-filling procedures such as pedo-transfer functions and down-core extrapolation of soil horizon data gives us opportunities to utilize more data points but it also introduces

Table 4. General characteristics of the soil maps constituting the spatial base of the NCSCDv2. Note that the polygon mean and median areas refer to the polygons of the original digitized soil maps, prior to further subdivision in the NCSCDv2 due to permafrost zonation, etc. This table is complementary to Table 1 in Hugelius et al. (2013).

Country or region[1]	Map scale	Mean/Median polygon area (km^2)	Total area (km^2)	Reference
Alaska	1 : 250 000	9778/3472	1 320 057	Soil Survey Staff (1997)
USA[2]	1 : 250 000	191/60	57 230	Soil Survey Staff (1997)
Canada	1 : 1 000 000	3598/1012	7 098 832	Tarnocai and Lacelle (1996)
Russia	1 : 2 500 000	6807/1007	16 442 294	Fridland (1988), Naumov (1993)
Kazakhstan	1 : 2 500 000	893/336	11 609	Uspanov (1976)
Mongolia	1 : 3 000 000	4004/1478	888 837	Dorzhgotov and Nogina (1990)
Greenland	1 : 7 500 000	179 639/42 919	2 155 664	Jakobsen and Eiby (1997)
Scandinavia	1 : 1 000 000	6042/697	259 794	European Soil Bureau (1999)
Iceland	1 : 1 500 000	1891/146	11 347	Arnalds and Gretarsson (2001)

[1] For Svalbard only highly generalized data are available. This region is uniformly classified as 70 % glacier, 20 % bedrock and 10 % turbel.
[2] Refers to the lower contiguous USA.

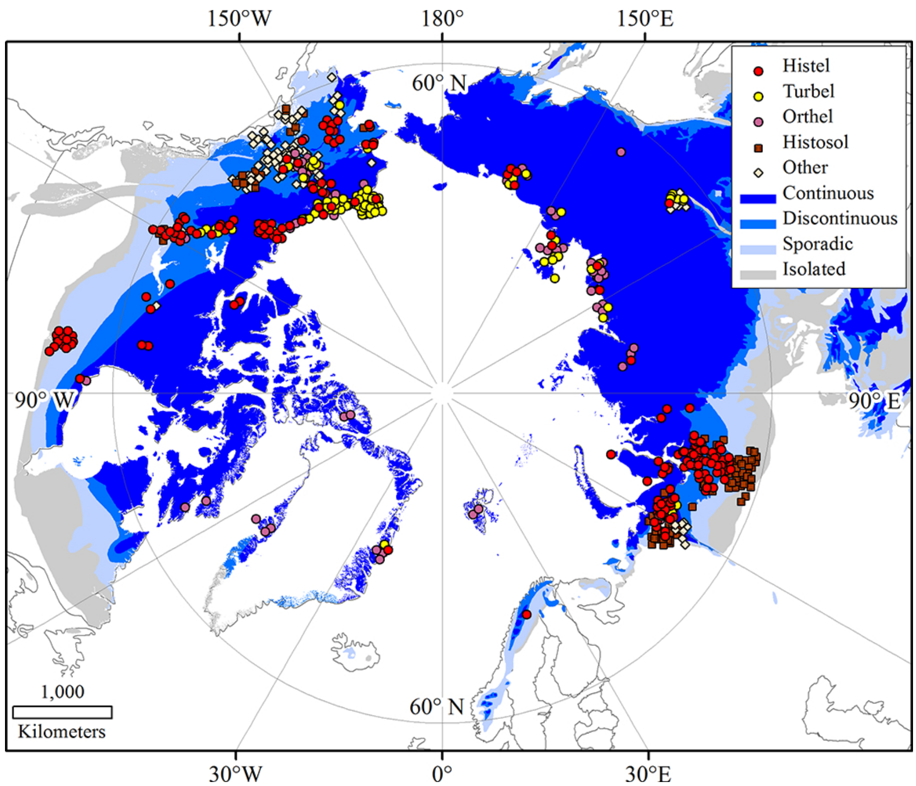

Figure 1. Geographical distribution of pedons with data in the 100–300 cm depth range in the northern circumpolar permafrost region. Pedons are shown according to NCSCD upscaling classes. Permafrost zonation from Brown et al. (2002). Exact pedon locations have been manipulated for cartographic representation so that all individual points are visible (Map projection: Azimuthal Equidistant, geodetic datum: WGS84).

uncertainties. This is especially true for those cases when default C-horizon SOC densities from the literature are used for sites with organic soils lacking field data from mineral soil horizons. However, we consider the magnitude of these uncertainties to be minor compared to the errors introduced by upscaling with a data set that is biased towards deep organic soils with very high SOC storage. Further, extrapolated deep data are calculated exclusively from pedons without any buried paleo-soil horizons underlying peat deposits and as no extrapolation of cryoturbated, SOC-rich, soil horizons has been done, the use of extrapolated data will err towards more conservative estimates. As the pedon data set accounts for the

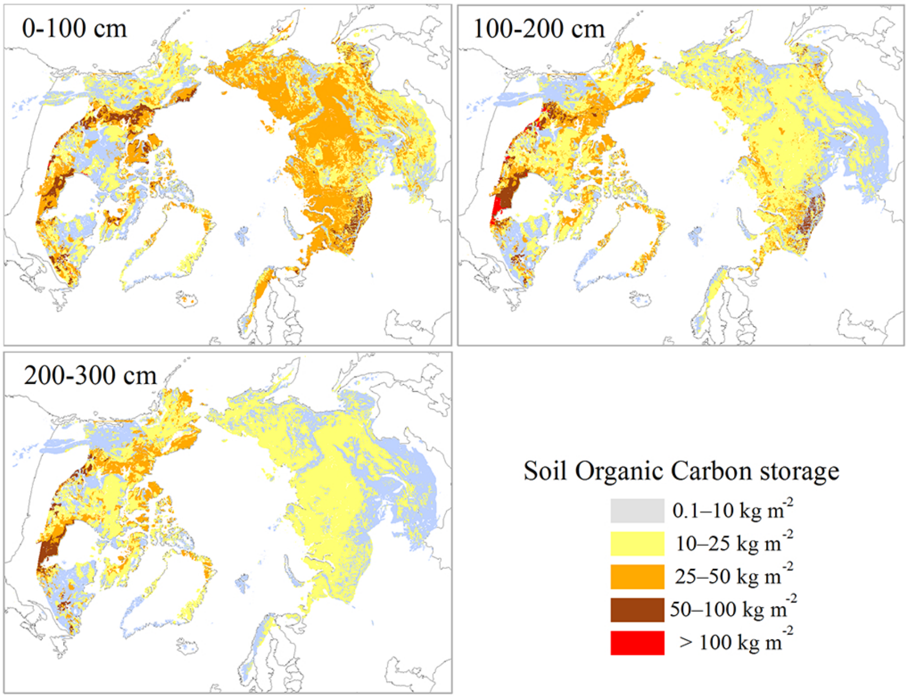

Figure 2. Estimated SOC storage (kg C m^{-2}) in the 0–100 cm, 100–200 cm and 200–300 cm depth ranges of the northern circumpolar permafrost region. Note that the data is normalised for total polygon area (including non-soil areas) unlike Figure 1 in Hugelius et al. (2013) where the data is normalised to polygon soil area (Map projection: Azimuthal Equidistant, geodetic datum: WGS84).

use of pedo-transfer functions, gap-filling and extrapolation, data users have the option of extracting and using only those pedons which suit their purpose.

Users of the NCSCDv2 should consider that the geographical spread of deep pedons remains highly uneven, with little or no representation in the permafrost affected regions of Central Asia, Scandinavia, Greenland, Svalbard and Eastern Canada, among other regions (Fig. 1). There are more pedon data available for the American sector in the 100–200 cm depth range (57 % of pedons), while there are more data from the Eurasian sector in the 200–300 cm depth range (58 % of pedons). This discrepancy is due to higher numbers of available pedons from organic soils in Eurasia (Table 1), in which all pedons extend to 300 cm depth because of the methodological differences between mineral and organic soils applied in this study (all organic soils extrapolated to full depth). The spatial base of the NCSCDv2 is compiled from many different regional soil maps of varying age, scale, classification systems and quality. Because of these differences in the original map scale, some regions are represented by more generalized soil data than other regions in the data set. Table 4 shows an overview of the spatial characteristics of the different regional soil maps in the NCSCDv2 (consider this table as complementary to Table 1 of Hugelius et al., 2013). See Hugelius et al. (2013) for more discussion on the implications of these differences for spatial applications using the NCSCDv2.

4 Conclusions and data access

The new pedon data set and its integration with the geospatial NCSCDv2 constitutes a significant addition to the knowledge of SOC stocks in the 100–300 cm depth range in soils across the circumpolar permafrost region. At the same time, this new data compilation shows that major gaps in spatial distribution of deep pedons remain (Fig. 1, pedon spreadsheet data). There are also large uncertainties surrounding the spatial extent of areas where soils are thinner than 3 m as well as the quantity and distribution of ground ice. These uncertainties need further investigation and could be targeted in future field campaigns.

The data set is the product of a wide collaborative effort to gather data from many different projects and research groups. Thanks to this approach the data set contains many pedons from regions that were previously not represented in circumpolar estimates of SOC stocks. There are still geographic limitations in the representation of soils but the three suborders of Gelisols and the Histosols are quite well characterized. This increases our understanding of and possibilities to model the unique processes that sequester large amounts of SOC in these high-latitude soils.

The compiled data set describing site characteristics and SOC stocks to the different reference depths (524 pedons in the 100–200 cm depth range and 356 pedons in the 200–300 cm depth range) and the updated NCSCDv2 is hosted by the Bolin Centre for Climate Research at Stockholm University, Sweden. An open access data-portal for all the described data sets is available online at http://bolin.su.se/data/ncscd/. The NCSCDv2 data set has the doi:10.5879/ECDS/00000002.

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