Soil organic carbon pools in the northern circumpolar permafrost region

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[1] The Northern Circumpolar Soil Carbon Database was developed in order to determine carbon pools in soils of the northern circumpolar permafrost region. The area of all soils in the northern permafrost region is approximately $18,782 \times 10^3$ km^2, or approximately 16% of the global soil area. In the northern permafrost region, organic soils (peatlands) and cryoturbated permafrost-affected mineral soils have the highest mean soil organic carbon contents ($32.2-69.6$ kg m^{-2}). Here we report a new estimate of the carbon pools in soils of the northern permafrost region, including deeper layers and pools not accounted for in previous analyses. Carbon pools were estimated to be 191.29 Pg for the $0-30$ cm depth, 495.80 Pg for the $0-100$ cm depth, and 1024.00 Pg for the $0-300$ cm depth. Our estimate for the first meter of soil alone is about double that reported for this region in previous analyses. Carbon pools in layers deeper than 300 cm were estimated to be 407 Pg in yedoma deposits and 241 Pg in deltaic deposits. In total, the northern permafrost region contains approximately 1672 Pg of organic carbon, of which approximately 1466 Pg, or 88%, occurs in perennially frozen soils and deposits. This 1672 Pg of organic carbon would account for approximately 50% of the estimated global belowground organic carbon pool.

1. Introduction

[2] The biosphere holds large carbon pools which, if destabilized through changes in climate and land use, can lead to accelerated emissions of greenhouse gases to the atmosphere [*Gruber et al.*, 2004]. Global climate-carbon models that account for only a few of these large pools show that carbon-climate feedbacks can lead to an average of 50 to 100 ppm additional CO_2 in the atmosphere by the end of this century [*Friedlingstein et al.*, 2006]. Therefore, it is important that future climate models include all major carbon pools and the processes that control their long-term carbon balance [*Canadell et al.*, 2007].

[3] Carbon stored in permafrost regions is one of the least understood and potentially most significant carbon-climate feedbacks because of the size of the carbon pools and the intensity of climate forcing at high latitudes [*Schuur et al.*, 2008]. The areal extent of permafrost soils and the carbon pools they contain have been underestimated since, in the past, the specific soil processes that lead to long-term carbon sequestration were not taken into account [*Post et al.*, 1982; *Jobbágy and Jackson*, 2000].

[4] There are a number of estimates of global soil organic carbon pools. Estimates for the $0-100$ cm depth include 1220 Pg [*Sombroek et al.*, 1993], 1395 Pg [*Post et al.*, 1982], 1462 to 1548 Pg [*Batjes*, 1996], 1502 Pg [*Jobbágy and Jackson*, 2000], and 1576 Pg [*Eswaran et al.*, 1993]. *Batjes* [1996] also reports global organic carbon pools for the $0-200$ cm depth ($2376-2456$ Pg) and *Jobbágy and Jackson* [2000] report global organic carbon pools for both the $100-200$ cm (491 Pg) and $200-300$ cm (351 Pg) depths.

[5] Few estimates exist of the size and spatial distribution of carbon pools in permafrost regions. *Post et al.* [1982] estimate that soils in the tundra zone contain, globally, approximately 191.8 Pg of organic carbon. This estimate, however, is based on only 30 samples to a depth of 100 cm. *Tarnocai et al.* [2003], using the Northern and Mid Latitudes Soil Database (NMLSD), estimated that the organic carbon pool in the $0-100$ cm depth of Cryosols (permafrost-affected soils) in the northern circumpolar

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region was approximately 268 Pg. Since then, however, the availability of new data sets in the Northern Circumpolar Soil Carbon Database (NCSCD) has shown that the NMLSD greatly underestimated the area of permafrost-affected soils in Eurasia.

[6] This paper reports new estimates of the organic carbon pools in both permafrost-affected and nonpermafrost soils in the northern circumpolar permafrost region. The new estimates, unlike those from previous analyses, include deeper layers, down to 300 cm, and additional carbon pools to depths greater than 300 cm for deltaic and yedoma deposits.

2. Materials and Methods

2.1. Northern Circumpolar Permafrost Region

[7] The study area encompasses the northern circumpolar permafrost region. This region is divided into four zones on the basis of the percentage of the land area underlain by permafrost (Figure 1): the Continuous Permafrost Zone ($\geq$90 to 100%), the Discontinuous Permafrost Zone ($\geq$50 to <90%), the Sporadic Permafrost Zone ($\geq$10 to <50%), and the Isolated Patches Permafrost Zone (0 to <10%) [*Brown et al.*, 1997].

2.2. Northern Circumpolar Soil Carbon Database

[8] The new estimates of organic carbon pools in soils of the permafrost region were calculated using the NCSCD (C. Tarnocai et al., 2007, Research Branch, Agriculture and Agri-Food Canada, Ottawa; available at http://wms1.agr.gc.ca/NortherCircumpolar/northercircumpolar.zip, hereinafter referred to as Tarnocai et al., unpublished data, 2007). This database contains over ten thousand polygons, with each polygon (mapping unit) containing one or more named soils or soil taxa that form the basis for determining the carbon pools. Data for North America and Europe are available in digital form in local soil databases that have been compiled from existing soil survey maps (Table 1). For remote areas in North America, where detailed soil maps are unavailable, pedon, climate, and vegetation data, together with high-quality LANDSAT imagery, were used to delineate polygons. For Russia, Greenland, Iceland, Kazakhstan, Mongolia, and Svalbard spatial soil information was digitized as it was only available as hard copy maps (Table 1).

[9] Data used to calculate carbon content (kg m^{-2}) were derived from multiple pedon databases (the pedon, or soil profile, is the basic soil unit used for describing, sampling, and classifying soils). The North American portion of the NCSCD was built up using 1038 pedons from northern Canada and 131 pedons from Alaska. The Eurasian portion of the NCSCD includes a newly assembled database containing soil organic carbon content data for 253 Russian pedons. Two existing databases also were used to obtain Russian data, the West Siberian Lowland Peatland GIS Data Collection, containing data for 90 peat cores [*Sheng et al.*, 2004; *Smith et al.*, 2000, 2004], and the Usa Basin database, containing information for 266 mineral and organic soils [*Kuhry et al.*, 2002; *Mazhitova et al.*, 2003]. Information from *Batjes* [1996] was also used for Eurasian soils

(including Russia), especially for those soils where no pedon information was available.

2.2.1. Computation of Soil Carbon Content

[10] Representative pedons for each soil taxon (Eurasia) or named soil (North America) were selected. Data for the various layers that compose each named soil (North America) and each soil taxon (Eurasia) were entered into the database and were used to calculate the carbon content of each named soil in the polygon.

[11] The Soil Organic Carbon Content (SOCC, kg m^{-2}) was calculated for each named soil (North America) and for the representative pedons for each soil taxon (Eurasia) using the formula

$$SOCC = C \times BD \times T \times (1 - CF),$$

where C is the organic carbon (% weight), BD is the bulk density (g cm^{-3}), T is the soil layer thickness, and CF is the coarse fragments and/or ice content (% weight). Using this information, the SOCC was then calculated for the 0–30, 0–100, 100–200 and 200–300 cm depths, or layers, for all pedons and these data were stored in the database. The percentages of the SOCC occurring in the 0–100, 100–200 and 200–300 cm depths of each major soil were then calculated on the basis of a total soil depth of 0–300 cm.

2.2.2. Computation of Soil Carbon Mass

[12] The Soil Organic Carbon Mass (SOCM, Pg) was then determined by multiplying the SOCC of the specific soil by the area of each such soil component in the polygon. When summed, these data provide information on the SOCM of each soil in each permafrost zone in the northern circumpolar region.

[13] For the North American portion of the study area, the SOCM for Histels and Histosols (peatlands) was calculated for the 0–100 cm depth and for the total depth of the peat deposit since this depth was included in the database. Since not all peat deposits in the Eurasian portion extend to 300 cm, the depth data obtained from the Usa and West Siberian databases [*Kuhry et al.*, 2002; *Sheng et al.*, 2004] were used to determine the percent distribution of peat in three depth categories, 0–100 cm (100%), 0–200 cm (50%), and 0–300 cm (10%). These percentages were then used to adjust the SOCM calculated for the various depths of the Eurasian peat soils (Histels and Histosols).

[14] Inceptisols were the only unfrozen mineral soils for which deep carbon data were available. The SOCM for these soils was calculated on the basis of data indicating that the 100–200 cm layer of the Inceptisols contained approximately 80% of the SOCC contained in the 0–100 cm layer and that the 200–300 cm layer contained no organic carbon. It was assumed that, like the Inceptisols, the other unfrozen mineral soils would also contain no soil organic carbon in the 200–300 cm layer.

2.3. Additional Deep Carbon Pools

[15] In addition to the soil carbon in the 0–300 cm depth, we are also reporting the two deep carbon pools (greater than 300 cm) described below.

[16] Yedoma deposits. These perennially frozen, loess-like (wind-blown) deposits, which have an average depth of approximately 25 m, contain large amounts of organic
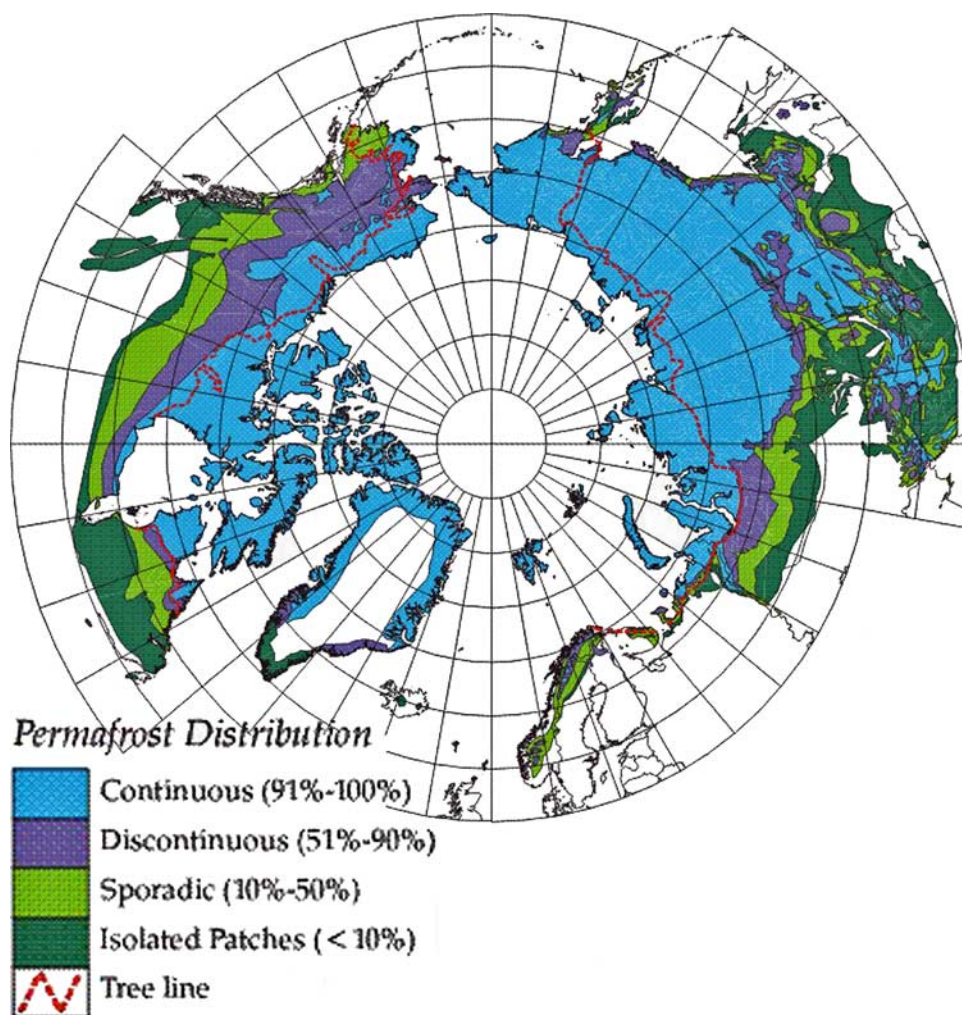
Figure 1. Northern circumpolar permafrost map (derived from information by *Brown et al.* [1997]).

carbon and ice, mainly in the form of ice wedges [*Zimov et al.*, 2006b]. Using SOCC data from the NCSCD, we calculated the SOCM for the 0–300 cm layer of these deposits. This value was then deducted from the value obtained for the 0–25 m depth in order to avoid double counting the 0–300 cm layer.

[17] River deltas. Information on the thickness of these alluvial deposits and the concentration of organic carbon in them is very scarce, except for the delta sediments of the

Mackenzie River in the Northwest Territories of Canada. Thus, this delta was used in this assessment as a model to estimate the carbon mass contained in the major northern deltas.

[18] The Mackenzie delta covers approximately 13,500 km^2, half of which is covered by shallow lakes and river channels. On the basis of five Mackenzie delta soil profiles [*Tarnocai et al.*, 1993; C. Tarnocai and H. Veldhuis, unpublished data, 1980, 1984], this delta has an SOCC of

Table 1. Data Sources for the NCSCD

Country or Region	Scale	Type of Data	Source
USA	1:250,000	Digital	*Soil Survey Staff* [1999]
Canada	1:1,000,000	Digital	C. Tarnocai and B. Lacelle (1996)[a]
Russia	1:2,500,000	Soil map	*Fridland* [1988] and *Naumov* [1993]
Kazakhstan	1:2,500,000	Soil map	*Uspanov* [1976]
Mongolia	1:3,000,000	Soil map	*Dorzhgotov and Nogina* [1990]
Greenland	1:7,500,000	Soil map	*Jakobsen and Eiby* [1997]
Scandinavia	1:1,000,000	Digital	*European Soil Bureau* [1999]
Iceland	1:1,500,000	Soil map	*Arnalds and Gretarsson* [2001]

[a]The Soil Organic Carbon Digital Database of Canada, Research Branch, Agriculture and Agri-Food Canada, Ottawa, 1996; available at http://wms1.agr.gc.ca/soilcarbonofCanada/soilcarbonofCanada.zip.

Table 2. Areas of All Soils in the Permafrost Zones

Permafrost Zones	Area (10^3 km^2)		
	North America[a]	Eurasia	Total
Continuous	2,868	7,255	10,123
Discontinuous	1,443	1,649	3,092
Sporadic	1,149	1,444	2,593
Isolated patches	1,186	1,788	2,974
Total	6,646	12,136	18,782

[a]Includes Greenland.

65 kg m^{-2}. The average thickness of delta deposits was calculated to be 50 m (on the basis of drill core data). In order to avoid double counting the upper 0–300 cm of the terrestrial portion of the delta, calculation of the SOCC was based on the 3–50 m depth. For deposits under water bodies, which are assumed to have an average depth of 5 m, the SOCC was calculated for a thickness of 45 m. It was also assumed that the rate of organic matter accumulation in recent decades was similar to that occurring in the past. In addition, it should be pointed out that the SOCC included only the carbon in the fine organic matter (<2 mm); coarse organic matter (logs, driftwood, etc.) was not included in these calculations.

2.4. Analytical Methods

[19] The carbon concentration (C%) was determined by using either the Walkley-Black method or the LECO CHN analyzer (after treating the samples with HCl to remove inorganic carbon) [*Sheldrick*, 1984]. Bulk density (BD) was determined by using core or clod samples, and coarse fragments (>2 mm size) were either estimated or a sieve method was used. It should be pointed out, however, that the methods used to obtain the analytical data were not always clearly identified in the original sources, a common problem in global studies of soil carbon pools.

3. Results

3.1. Permafrost-Affected and Nonpermafrost Soils

3.1.1. Soil Area

[20] The total area of soils in the northern circumpolar permafrost region is $18,782 \times 10^3$ km^2, with approximately 65% of the area occurring in Eurasia and 35% in North America and Greenland. The largest portion of this soil area (54%) lies within the Continuous Permafrost Zone, with the remaining 46% being split approximately equally between the Discontinuous, Sporadic, and Isolated Patches permafrost zones (Table 2). The distribution of the various soil orders that occur in this region is shown in Figure 2.

[21] Peatlands, which are a common feature of all permafrost zones, cover about 3556×10^3 km^2, or approximately 19% of the soil area of the northern circumpolar permafrost region (Table 3). The area of peatlands in the permafrost region of North America is 1048×10^3 km^2 and in Eurasia, 2508×10^3 km^2.

3.1.2. Carbon Content

3.1.2.1. Carbon Content at 0–100 cm

[22] The mean SOCC values calculated for the 0–100 cm depth in soils of the northern permafrost region are given in Table 4 and their distribution is shown in Figure 3. Histels (perennially frozen peatland soils, Gelisols) and Histosols

(unfrozen peatland soils) have the highest SOCC values, with mean values of 66.6 kg m^{-2} (maximum 133 kg m^{-2}) for Histels and 69.6 kg m^{-2} (maximum 130 kg m^{-2}) for Histosols. The mean SOCC values for mineral Gelisols are 22.6 kg m^{-2} (Orthels) and 32.2 kg m^{-2} (Turbels), with Turbels having the highest mean and maximum (126 kg m^{-2}) SOCC values for mineral soils. In some cases these mean and maximum values for Turbels are as much as three times those for unfrozen mineral soils (Table 4).

[23] The standard deviation (SD) was greatest for Histels (53.3) and Histosols (56.9) (Table 4), probably because of the variable depth of peat deposits, the different types of peat materials, the degree of decomposition, and the mineral (ash) content. Turbels (27.4), Orthels (21.4), and Spodosols (20.2) had the second greatest standard deviations. Their relatively large values are probably due to the various thicknesses of surface organic material associated with them and, for Turbels, also to variability in the amounts of cryoturbated organic materials they contain.

3.1.2.2. Carbon Content at 0–300 cm

[24] There are a number of processes that cause carbon to be incorporated into the deeper layers of soils: cryoturbation for Turbels, repeated deposition of organic-rich material for Orthels (alluvium), and long-term deposition of organic materials for Histels and Histosols [*Bockheim*, 2007; *Tarnocai and Stolbovoy*, 2006].

[25] SOCC values for those soils with deeper layers (below 100 cm) were calculated on the basis of a limited number of available pedons (Table 5). The lowest SOCC values occur in Orthels (without alluvium), a noncryoturbated, permafrost-affected soil, and in Inceptisols, a nonpermafrost soil. Neither of these soils has carbon occurring at depths below 200 cm because they have no mechanisms other than deep roots, leaching, or burial to move carbon into the deeper soil layers. In addition, since the vegetation on these soils is generally shallow rooted, it contributes very little or no carbon to the deeper soil layers.

[26] Turbels contain approximately 38% of their carbon in the upper 100 cm, 33% at 100–200 cm, and 28% at 200–300 cm, representing a 5% decrease in carbon content per 100 cm. Orthels (alluvium) have about 80% of their carbon distributed equally between the upper two layers (0–200 cm), with approximately 20% in the third layer (200–300 cm). These levels of carbon probably also occur at depths greater than 300 cm in some of these deposits.

[27] For Histosols the SOCC is approximately evenly distributed in the three layers. The slight variation is probably due to the origin of the peat material and amount of mineral content. The distribution of carbon in Histels is similar to that in Histosols, but the carbon content drops somewhat in the third layer, probably because of the increased ice content in this layer. The levels of carbon in the 200–300 cm depth of these soils indicate that similar carbon levels probably also occur at greater depths, depending on the total depth of the peat deposit.

3.1.3. Carbon Mass

3.1.3.1. Carbon Mass at 0–100 cm

[28] The total soil organic carbon mass (SOCM) in the 0–100 cm depth is 495.80 Pg (Table 6) with peat deposits containing approximately 150.46 Pg, or 30% of this mass
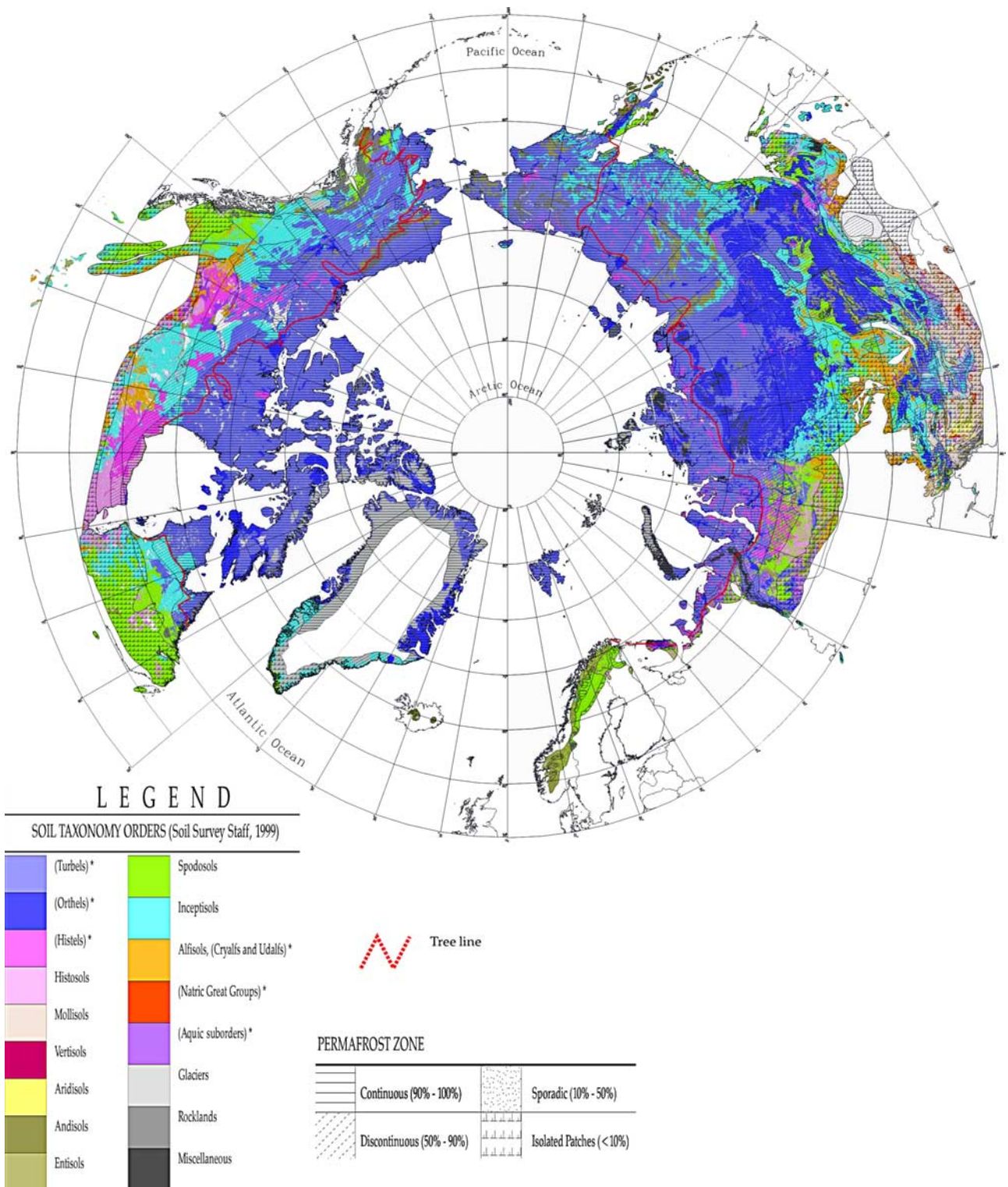
Figure 2. Distribution of soils in the northern circumpolar permafrost region based on the NCSCD (Tarnocai et al., unpublished data, 2007). Note that the legend entries followed by asterisks refer to another U.S. taxonomic level.

Table 3. Areas of Peatlands in the Permafrost Zones

Permafrost Zones	Peatland Area (10^3 km^2)		
	North America[a]	Eurasia	Total
Continuous	228	1895	2123
Discontinuous	272	159	431
Sporadic	321	240	561
Isolated patches	227	214	441
Total	1048	2508	3556

[a]Includes Greenland.

(Table 7). Approximately two thirds (67%) of the total soil organic carbon mass is in the Eurasian portion of the northern circumpolar permafrost region with the remainder (33%) in the North American portion. The Continuous Permafrost Zone contains 60% of the SOCM and the other three zones together contain 40%.

3.1.3.2. Carbon Mass at 100–300 cm

[29] The total soil organic carbon mass (SOCM) in the 100–300 cm depth is 528.2 Pg (Table 8). For Turbels, approximately 36% of the SOCM occurs in the first 100 cm and 64% occurs in the 100–300 cm layers. Thus, two thirds of the SOCM is missed if only the 0–100 cm layer is sampled. This explains, to some extent, the smaller estimates in previous analyses. For Orthels, all of the SOCM occurs in the 0–200 cm layers with approximately 97% in the first 100 cm and 3% in the 100–200 cm layer (Table 8).

[30] For unfrozen mineral soils, deep soil data is available only for the Inceptisols. For these soils, the first 100 cm contains approximately 68% of the SOCM and the 100–200 cm layer contains approximately 32% (Table 8), with no organic carbon occurring deeper than 200 cm. The carbon in these soils originated dominantly from roots and, to a lesser extent, from dissolved illuviated organic matter. Since these soils are associated with shallow-rooted vegetation, most of the organic carbon occurs in the upper layer of the soil.

3.2. Additional Carbon Pools

[31] The organic carbon pools in all soils in the northern permafrost region were determined uniformly to a depth of 300 cm. The deltaic, or alluvial, deposits and yedoma deposits, however, cover vast areas and contain large amounts of organic carbon below the 300 cm depth. While the future fate of these deep carbon pools is beyond the scope of this paper, mechanisms currently exist that can
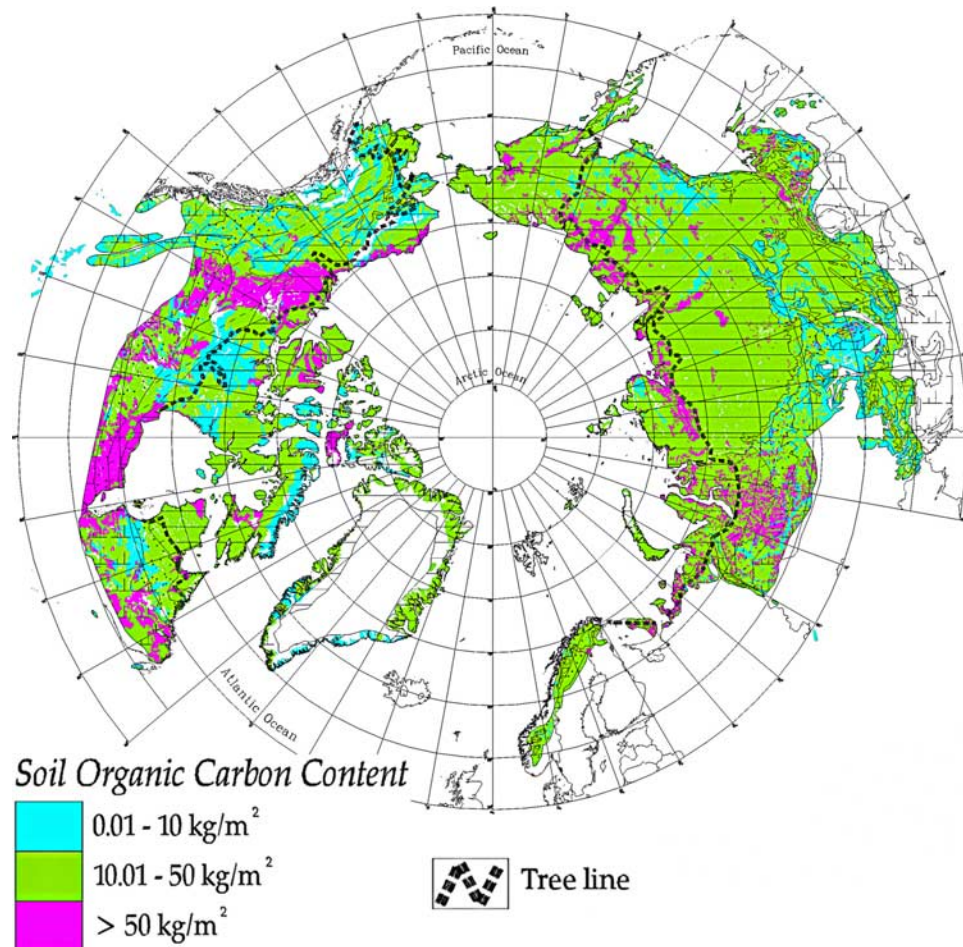

Figure 3. Distribution of soil organic carbon contents in the northern circumpolar permafrost region based on the NCSCD (Tarnocai et al., unpublished data, 2007).

Table 4. Mean Soil Organic Carbon Contents for the Upper 0–100 cm in Soils

Soil[a]	SOCC (kg m^{-2})			
	Mean	Range	SD	Number of Pedons
Gelisols				
Histels	66.6	21–133	53.3	87
Turbels	32.2	1–126	27.4	256
Orthels	22.6	0.1–65	21.4	131
Histosols	69.6	6–130	56.9	417
Andisols	25.4[b]	unknown	8.3	unknown
Spodosols	24.7	2–110	20.2	6
Aquic suborders	20.1	1–94	9.7	531
Inceptisols	15.3	0.5–93	9.4	871
Vertisols	13.5	6–27	7.3	11
Entisols	9.9	6–75	15.8	198
Mollisols	9.6	1–42	8.3	422
Natric suborders	9.1	6–40	7.6	67
Alfisols	8.9[b]	unknown	6.9	533
Aridisols	3.0[b]	unknown	6.6	unknown

[a]U.S. taxonomy [*Soil Survey Staff*, 1999].
[b]SOCC data are from *Batjes* [1996].

rapidly expose deep permafrost carbon to thaw [*Schuur et al.*, 2008]. Thus, the first step is to quantify the size of these deep permafrost carbon pools.

3.2.1. Yedoma Deposits

[32] These deposits, which were formed by the deposition of sediments in unglaciated areas during glacial periods, occur in areas that, at that time, were covered by a mammoth steppe-tundra ecosystem. According to *Zimov et al.* [2006b], these perennially frozen yedoma sediments cover more than 1 million km^2, have an average depth of approximately 25 m, and contain 2–5% organic carbon. In continental areas, the yedoma sediments contain 1–5% organic carbon by dry mass (maximum 30%) [*Zimov et al.*, 2006a; *Dutta et al.*, 2006] and in wetter areas they contain 2–30% organic carbon [*Schirrmeister et al.*, 2002]. Using an average carbon concentration of 2.6%, *Zimov et al.* [2006b] estimated that that these sediments contain approximately 500 Pg of carbon, subsequently revised to 450 Pg [*Zimov et al.*, 2006a]. On the basis of this revised estimate, yedoma sediments were found to contain 407 Pg of organic carbon in the 3–25 m depth.

3.2.2. Deltaic Deposits

[33] The major river deltas included are those of the Yukon and Colville rivers in Alaska, USA, the Mackenzie River in the Northwest Territories of Canada, and the Lena, Pechora, Ob, and Kolyma rivers in northern Russia. Sedi-

ments deposited by rivers contain organic matter. Since the deposition is recurring, these freshly deposited materials are buried by the new deposits and, in most cases, become perennially frozen. This deposition is especially active on the river deltas, where the deposited sediments can reach several tens of meters in thickness. Although little information, other than the area they cover, is available for the major deltas of the circumpolar permafrost region, information on the thickness of the deposits and the concentration of organic carbon in them is available for the Mackenzie River delta. Therefore, this delta was used as a model to estimate the carbon mass in the major northern deltas. On the basis of this model, we estimated that the seven major river deltas contain a total of 241 Pg of SOCM in layers deeper than 300 cm (Table 9).

4. Discussion

[34] Our estimates indicate that the northern circumpolar permafrost region contains 1024.00 Pg of soil organic carbon in the surface 0–300 cm depth, with an additional 648 Pg of carbon locked in deep layers of yedoma (407 Pg) and deltaic (241 Pg) deposits. In total, the northern circumpolar permafrost region contains 1672 Pg of organic carbon, of which 1466 Pg (88%) occurs in perennially frozen soils and deposits. This 1672 Pg of organic carbon is a significantly larger pool than previous estimates have given. Thus, the northern circumpolar permafrost region contains approximately 50% of the reported global belowground organic carbon pool.

[35] Previous northern latitude nonpeatland soil carbon pools were estimated to be in the range of 150–191 Pg carbon for boreal forest [*Apps et al.*, 1993; *Jobbágy and Jackson*, 2000], and 60–144 Pg carbon for tundra [*Apps et al.*, 1993; *Gilmanov and Oechel*, 1995; *Jobbágy and Jackson*, 2000; *Oechel et al.*, 1993]. Some widely cited estimates quantify the soil carbon pool in northern peatlands as 419–455 Pg [*Gorham*, 1991; *Apps et al.*, 1993]. The difference, in large part, between our new estimate and previous estimates is the recognition and quantification of significant carbon below 100 cm outside of peatlands, although direct comparisons need to be made with caution because of differences among studies.

[36] Estimates of global soil organic carbon pools for the 0–100 cm depth range between 1220 and 1576 Pg [*Eswaran et al.*, 1993; *Sombroek et al.*, 1993; *Batjes*, 1996]. *Batjes* [1996] reported that soil organic carbon pools for the 0–200 cm depth were 2376–2456 Pg while *Jobbágy*

Table 5. Mean Soil Organic Carbon Contents and Ranges for the Various Soil Layers to a Depth of 300 cm

Soil	SOCC[a] (kg m^{-2})				Number of Pedons
	0–100 cm	100–200 cm	200–300 cm	Total (0–300 cm)	
Turbels	61.0 (28–89)	53.1 (22–106)	45.1 (30–60)	159.2	8
Orthels (without alluvium)	4.5 (0.5–9)	1.6 (0.1–3)	0	6.1	4
Orthels (alluvium)	142.6 (142–143)	142.5 (142–143)	67.0 (66–68)	352.1	2
Histels	67.2 (31–171)	62.0 (22–128)	41.5 (20–94)	170.7	13
Histosols	64.7 (61–67)	62.6 (16–88)	67.5 (16–92)	194.8	15
Inceptisols	12.6 (7–22)	10.3 (1–23)	0	22.9	3

[a]Calculated using only the deep pedons, so values do not match those in Table 4 for the 0–100 cm depth of the same soils. Ranges are given in parentheses.

Table 6. Organic Carbon Mass at Depths of 0–30 cm and 0–100 cm in All Soils

| Permafrost Zones | SOCM (Pg) | | | | |
| | North America[a] | | Eurasia | | Total |
	0–30 cm	0–100 cm	0–30 cm	0–100 cm	0–100 cm
Continuous	31.2	78.3	79.2	220.2	298.5
Discontinuous	12.2	29.6	13.3	37.7	67.3
Sporadic	10.9	26.2	15.5	36.7	62.9
Isolated patches	12.6	30.6	16.4	36.5	67.1
Total	66.9	164.7	124.4	331.1	495.8

[a]Including Greenland.

and Jackson [2000] indicated that the pools for this depth were 1993 Pg and for the 0–300 cm depth were 2344 Pg. These global estimates indicate that soils in the northern circumpolar permafrost region contain approximately 33% of the global organic carbon in the 0–100 cm depth and 44% of that in the 0–300 cm depth.

4.1. Carbon Pools and Data Uncertainty

[37] The spatial and soil data used in this paper were derived from a number of sources that had different rates of accuracy and uncertainty. Therefore, assigning a single confidence value to the new carbon estimate for the entire northern circumpolar region would not be realistic. Instead, we have divided this area into two subregions and have assigned the confidence levels used in the IPCC Fourth Assessment. As a result, we have medium to high confidence (66–80%) in the North American data (for the 0–100 cm depth) since the carbon database, the largest data set, was tested by the methods indicated below and low to medium confidence (33–66%) in the equivalent Eurasian data, a smaller data set (section 2.2). We have very low to low confidence (<33%) in the soil carbon estimates for the deeper soil layers and for the other deposits since they are based on an even smaller data set (Table 5).

[38] Data available for estimating carbon pools are limited and are associated with numerous gaps and uncertainties. SOCM data generated for the 0–100 cm depth in soils is based on the largest pedon data set, especially for the North American portion of the permafrost area. However, SOCM data generated for greater depths are based on smaller data sets and will require future improvements.

Table 7. Soil Organic Carbon Mass for the Total Depth of the Peat Deposits in North America and Eurasia

| Permafrost Zones | SOCM[a] (Pg) | | | | |
	Canada[b]	Alaska[c]	North America	Eurasia	Total
Continuous	21.8	1.5	23.3	120.9	144.2
Discontinuous	26.6	0.8	27.4	10.7	38.1
Sporadic	30.6	0.3	30.9	16.1	47.0
Isolated patches	32.9	0	32.9	15.1	48.0
Total	111.9	2.6	114.5	162.8	277.3

[a]Calculated for the total depth of the peat deposit.
[b]Calculated using the Peatlands of Canada database (C. Tarnocai et al., 2005, Research Branch, Agriculture and Agri-Food Canada, Ottawa; available at http://wms1.agr.gc.ca/peatlandofCanada/peatlandofCanada.zip).
[c]Calculated using the Northern and Mid-Latitude Soil Database [*Cryosol Working Group*, 2004].

Table 8. Soil Organic Carbon Mass Values to a Depth of 300 cm for Major Soil Groups

| Soil[a] | SOCM (Pg) | | | |
	0–100 cm	100–200 cm	200–300 cm	0–300 cm
Gelisols	351.5	–	–	818.0
Turbels	211.9	207.2	162.2	581.3
Orthels	51.3	1.7	0	53.0
Histels	88.3	–	–	183.7[b]
Alfisols	4.6	1.4	0	6.0
Inceptisols	23.2	10.8	0	34.0
Spodosols	28.4	9.4	0	37.8
Aquic suborders	4.2	2.8	0	7.0
Mollisols	10.7	2.1	0	12.8
Entisols	6.6	2.1	0	8.7
Histosols	62.2	–	–	94.3[b]
Aridisols	1.3	0.3	0	1.6
Vertisols	0[c]	0	0	0
Andisols	2.9	0.7	0	3.6
Natric suborders	0.2	0	0	0.2
Total	495.8	–	–	1024.0

[a]U.S. taxonomy [*Soil Survey Staff*, 1999].
[b]Calculated for the total depths of the various peat deposits but not separated into layers for depths >100 cm.
[c]SOCM <0.0001 Pg.

[39] The North American soil organic carbon estimates presented in this paper were generated using data from the NCSCD, which is an updated version of the Canadian Soil Organic Carbon Database (CSOCD). *Bhatti et al.* [2002] compared carbon estimates generated by the CSOCD with carbon values generated by both the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS2) and the Boreal Forest Transect Case Study (BFTCS). They found that the CSOCD generated slightly lower carbon values than the CBM-CFS2 carbon model, but that there was good agreement between CSOCD- and BFTCS-generated values.

[40] Although SOCM data are available for the permafrost region in Eurasia, *Stolbovoi* [2000] provides only estimates of 297 Pg for the 0–100 cm depth and 373 Pg for the 0–200 cm depth for the SOCM of all soils in Russia. In order to shed some light on the reliability of the Eurasian soil organic carbon data, organic soils (Histels and unfrozen

Table 9. Areas and Total Organic Carbon Mass Below 300 cm for Major Deltas in the Northern Permafrost Region

River Delta	Area (km²)	Total Carbon Mass[a] (Pg)
Yukon	5,280[b]	16
Colville	1,687[b]	5
Mackenzie	13,500[c]	41
Lena	43,563[b]	131
Pechora	8,737[b]	26
Ob	4,000[d]	12
Kolyma	3,000[e]	10
Total	79,767	241

[a]Carbon masses for all deltas were determined using the carbon content calculated for the Mackenzie River Delta.
[b]Information on major world deltas is available from J. M. Coleman and O. K. Huh (unpublished data, 2004, available at http://www.geol.lsu.edu/WDD/PUBLICATIONS/C&Hnasa04/C&Hfinal04.htm).
[c]Mackenzie Delta information is available from *Mackenzie River Basin Board* [2004].
[d]Ob River data are available from The Unabridged Hutchinson Encyclopedia, available at http://encyclopedia.farlex.com/Ob+River.
[e]*Pavlov et al.* [1994].

organic soils) were used as a test since this data is available for Russian peatlands, which account for most of the peatlands in Eurasia. In Russia, organic soils and peatlands, by definition, contain 30 cm or more of organic material (in North America organic soils and peatlands contain 40 cm or more of organic material). Various estimates of the areas and SOCM of Russian peatlands are 1162×10^3 km^2 and 94 Pg [*Stolbovoi*, 2000], 1650×10^3 km^2 and 215 Pg [*Botch et al.*, 1995], and 2730×10^3 km^2 and 118 Pg [*Efremov et al.*, 1998]. For comparison, our paper gives an estimated area of 2508×10^3 km^2 (Table 3) and an SOCM of 162.80 Pg (Table 7) for the total depth of the peat deposit in the permafrost zones of Eurasia. It is evident that the areas and carbon masses in published estimates vary widely ($1162-2730 \times 10^3$ km^2 and 94–215 Pg). These large variations occur because of the poor inventory and limited amount of reliable pedon data available for these soils. This supports the levels of accuracy for estimates of peat carbon established by *Efremov et al.* [1998] of ±10–15 percent for the European part of Russia and ±20–30 percent for the Asian part of the country.

[41] The SOCC values of unfrozen and noncryoturbated frozen mineral soils in the permafrost region are similar to those of soils in the temperate region. In these soils, the organic matter that is deposited on the soil surface is not affected by cryoturbation. Some soluble organic matter may move downward, but there is no mechanism for moving organic matter from the surface into the deeper soil layers and preserving it from decomposition and wildfires. Since most of the belowground carbon in these soils originates from roots, its residence time is thus relatively short.

4.2. Vulnerability of Carbon in Permafrost

[42] Permafrost degradation resulting from warmer temperatures at high latitudes and changes in precipitation (e.g., increased snowfall leads to increased degradation) is now widely reported [*Payette et al.*, 2004; *Camill*, 2005; *Jorgenson et al.*, 2006]. Projections show that almost all near-surface permafrost will disappear by the end of this century [*Lawrence et al.*, 2008] with the active layer deepening at a decreasing rate as we move northward.

[43] Both depth and spatial distribution of permafrost degradation will result in different degrees of vulnerability of the various carbon pools as reported by *Schuur et al.* [2008]. Carbon in near-surface permafrost is, and will be, the most vulnerable pool during this century given the retreat of permafrost to deeper layers. However, as permafrost thaws, the newly formed thermokarst lakes act as conduits of both surface heat to deeper layers and deep methane to the surface [*Zimov et al.*, 2006a].

[44] Modeling work also suggests that global warming could trigger an irreversible process of thawing as self-sustaining heat generated by microbial activity leads to deep soil respiration in a multicentury timeframe. This process, which could continue even after warming has stabilized or stopped, would result in long-term sustained chronic emissions of CO_2 and CH_4 [*Khvorostyanov et al.*, 2008]. Since the yedoma deposits reported in this study occur in cold permafrost, they are unlikely to show self-sustaining heat generation although they can still be significant carbon

sources of 0.2 Pg C a^{-1} (or 1 Pg C a^{-1} of CO_2-eq) into the next century [*Khvorostyanov et al.*, 2008].

[45] Global warming, thermokarst formation, and fire frequency will push the net carbon balance and full radiative forcing of permafrost degradation in directions often determined by regional conditions. This heterogeneity of the regional net carbon balance is well illustrated by the decrease in the net ecosystem productivity (NEP) in warm and dry/wet regions in Alaska over the past two decades, while NEP increased in the colder and wetter regions [*Thompson et al.*, 2006]. Fire will trigger additional thermokarst collapse, accelerating permafrost degradation and subsequent peat formation [*Myers-Smith et al.*, 2008]. Not taking into account these complex interactions, *Zhuang et al.* [2006] estimated net emissions from thawing permafrost in the northern high latitudes at 7–17 Pg in 100 years, while *Davidson and Janssens* [2006] report a potential carbon loss of 100 Pg C over the same timeframe.

[46] The significance of having more accurate information about the distribution of carbon in permafrost and the size of the overall pool is well illustrated by the following example. *Gruber et al.* [2004] estimated that as much as 100 Pg of carbon could be released from thawing permafrost over this century, a 25% loss from the 400 Pg carbon pool on which they based their calculations. Extrapolating their analyses using our new carbon pool estimate would yield a potential carbon loss four times greater. This alone would account for the entire upper range of the multiple carbon-climate feedbacks currently estimated by climate models [*Friedlingstein et al.*, 2006]. Even taking into account the possibility that this is an extreme case and that there will be other mechanisms which might remove carbon from the atmosphere (e.g., enhanced plant uptake and northward forest migration), the potential for significant feedbacks from permafrost carbon could be realized with only a small fraction of the total pool being thawed and released to the atmosphere. More recently, *Raupach and Canadell* [2008], using a simple carbon-climate model and a smaller frozen carbon pool (1000 Pg), showed that, if 10% of the permafrost were to thaw, the feedback from CO_2 emissions could result in an additional 0.7°C and a CO_2 increment of 80 ppm by the end of this century. Landscape and small-scale processes, which control the thawing of permafrost and the subsequent decomposition of organic matter, are the key processes that limit our ability to constrain the future net carbon balance of permafrost regions.

5. Conclusions

[47] The data presented in this paper indicate the large amount of organic carbon stored in soils of the northern circumpolar permafrost region. These new estimates will help to provide a more reliable prediction for the effect of global change and human activities on this carbon.

[48] 1. Northern circumpolar soils are estimated to cover approximately $18,782 \times 10^3$ km^2 and contain about 191 Pg of organic carbon in the 0–30 cm depth, 496 Pg of organic carbon in the 0–100 cm depth, and 1024 Pg of organic carbon in the 0–300 cm depth. Our estimate for the first

meter of soil alone is approximately double that reported in previous analyses.

[49] 2. We also estimated the organic carbon pools in less known and studied frozen deposits. These are the deltaic deposits and the Siberian yedoma sediments, which contain approximately 648 Pg of organic carbon at depths greater than 300 cm. The 0–300 cm carbon pool estimates for these deposits are included in the estimates given in point 1.

[50] 3. In the northern circumpolar permafrost region all carbon pools combined contain approximately 1672 Pg of organic carbon, which is approximately 50% of the global belowground organic carbon and almost an order of magnitude higher than that used in many global biogeo-chemical and climate modeling studies (200–300 Pg C from the FAO soil database).

[51] 4. Our confidence in the North American soil carbon estimates for the 0–100 cm depth is medium to high (66–80%) while our confidence in the equivalent Eurasian portion is low to medium (33–66%) since the estimates are based on a smaller data set. Our confidence in carbon estimates for the deeper soils layers and for the other deposits is the lowest (<33%) since they are based on even smaller data sets.

[52] 5. The data reported in this study show that the amount of carbon stored in northern circumpolar soils and, thus, the potential for carbon-climate feedbacks from this region, where the greatest global warming is predicted to occur, has been hugely underestimated. This study more than doubles the size of the carbon pools in the northern circumpolar region, the area that can ultimately be exposed to new environmental conditions more amenable to decom-position of organic matter and, therefore, to its associated release of carbon dioxide or methane.

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