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Determining carbon stocks in Cryosols using the Northern and Mid Latitudes Soil Database

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ABSTRACT: The distribution of Cryosols and their carbon content and mass in the northern circumpolar area were estimated by using the Northern and Mid Latitudes Soil Database (NMLSD). Using this database, it was estimated that, in the Northern Hemisphere, Cryosols cover approximately $7769 \times 10^3\,km^2$ and contain approximately 119 Gt (surface, 0–30 cm) and 268 Gt (total, 0–100 cm) of soil organic carbon. The 268 Gt organic carbon is approximately 16% of the world's soil organic carbon. Organic Cryosols were found to have the highest soil organic carbon mass at both depth ranges while Static Cryosols had the lowest. The accuracy of these carbon values is variable and depends on the information available for the area. Since these soils contain a significant portion of the Earth's soil organic carbon and will probably be the soils most affected by climate warming, new data is required so that more accurate estimates of their carbon budget can be made.

1 INTRODUCTION

Soils are the largest source of organic carbon in terrestrial ecosystems. Estimates of this carbon range from 1115 to 2200 Pg (Batjes 1996, Eswaran et al. 1993, Sombroek et al. 1993). The abundance and composition of organic carbon (organic matter) plays an important role in soil and ecosystem processes. Soil organic carbon is very dynamic and can be changed markedly by both human activities such as land use, deforestation and biomass burning and natural forces such as wildfires and global warming.

In Arctic ecosystems Cryosols, or permafrost-affected soils, contain by far the largest amounts of organic carbon when compared to other components of these ecosystems. Not only do Cryosols contain large amounts of organic carbon, but they also sequester carbon as a result of cryogenic processes. In addition, areas with Cryosolic soils are predicted to be the areas most affected by global warming (Woo et al. 1992, Mitchell et al. 1990).

Although ninety-nine percent of the world's Cryosols occur in the Northern Hemisphere (Tarnocai & Campbell, in press), little information is available about the amount of organic carbon these soils contain. In order to compile the information available for these soils and identify the gaps in information, the Northern and Mid Latitudes Soil Database (NMLSD) (Cryosol Working Group 2001) was developed by the Cryosol Working Group of the International Permafrost Association (IPA) and the International Union of Soil Science (IUSS). Using this spatial database, which is in Arc/Info format, the Soils of Northern and Mid Latitudes (Tarnocai et al. 2002a) and Northern Circumpolar Soils (Tarnocai et al. 2002b) maps were generated.

In this paper the NMLSD was used to estimate the organic carbon contents and masses of Cryosols in the northern circumpolar area.

2 MATERIALS AND METHODS

2.1 *Area*

North America, Greenland, all of Europe and northern Asia are included in the NMLSD. The soil information in this database was derived from spatial information at scales of 1:1,000,000 or 1:2,000,000. This information was then correlated and integrated into a seamless database covering the northern and mid latitudes. For this study, the permafrost, or Cryosolic soil, area of the NMLSD will be used. This area is referred to as the northern circumpolar area.

2.2 *Database structure*

The NMLSD contains a polygon table that includes the polygon ID (identification number), area of the polygon and the percent distribution of soils, rocklands, glaciers and miscellaneous land types. This table is then linked to the original databases as shown in Figure 1.

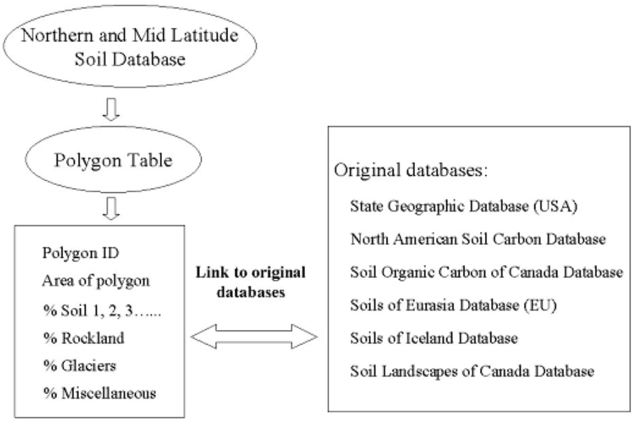

Figure 1. NMLSD database structure.

2.3 *Methods and data sources*

For the North American portion of the database, the soil organic carbon content was calculated on the basis of sampled pedons (soil profiles) that were included in the carbon layer table of the North American Soil Carbon database (Kimble et al. 2000).

Soil organic carbon content (SOCC, $kg\,m^{-2}$) was calculated for each soil layer by the formula:

$$SOCC = C * BD * T * CF \quad (1)$$

where C = organic carbon percent, BD = bulk density ($g\,cm^{-3}$), T = depth of soil layer or horizon (cm) and CF = percent coarse fragments. The SOCC was then recalculated for standard depths of 0–30 cm (surface) and 0–100 cm (total).

For the Eurasian portion of the database, the SOCC was calculated for Turbic, Static and Organic Cryosol pedons from eastern, western and central Siberia using the above formula. This information was then used to recalculate the SOCC for the standard depths.

For Greenland, the organic carbon content for Cryosols were extrapolated from North American data for the High Arctic and used to calculate carbon masses.

Soil organic carbon masses (SOCM) were determined by multiplying the soil organic carbon content of the soil by the area of each soil component in the polygon.

2.4 *Terminology*

The Canadian soil classification terminology (Soil Classification Working Group 1998) is used in this paper for the classification of permafrost-affected soils. In the Canadian system, permafrost-affected soils are classified in the Cryosolic Order, which is further subdivided into the Turbic, Static and Organic great groups. In the US soil taxonomy (Soil Survey Staff 1999) these soils belong to the Gelisol Order, which is further subdivided into the Turbel, Orthel and Histel suborders (Table 1).

Table 1. Great groups of the Cryosolic Order and suborders of the Gelisolic Orders and their characteristics.

Canadian*	American**	Soil characteristics
Turbic Cryosol	Turbels	Cryoturbated, permafrost within 2 m of the surface
Static Cryosol	Orthels	Non-cryoturbated, permafrost within 1 m of the surface
Organic Cryosol	Histels	Organic materials >40 cm thick, permafrost within 1 m of the surface

* Soil Classification Working Group 1998.
** Soil Survey Staff 1999.

The SOCC refers to the concentration of carbon in a one metre square column of soil. It is expressed as $kg\,m^{-2}$ for either surface carbon (30 cm deep column) or total soil organic carbon content (100 cm deep column).

The SOCM is expressed as kilograms (kg) or gigatonnes (Gt) of carbon and refers either the surface carbon mass (0–30 cm) or the total organic carbon mass (0–100 cm). Note that 1 Gt equals 1 Pg.

3 RESULTS

3.1 *Area of Cryosols*

Cryosols cover $7769 \times 10^3\,km^2$ in the northern circumpolar area (Fig. 4), with coverage of $4162 \times 10^2\,km^2$ in Eurasia and $3607 \times 10^2\,km^2$ in North America (including Greenland). Turbic Cryosols are the dominant Cryosols in North America, but in Eurasia Organic Cryosols are the dominant permafrost-affected soils (Table 2). The distribution of Cryosols in the various permafrost zones is shown in Figure 2.

3.2 *Organic carbon content*

The means and ranges of SOCC values for the 0–30 cm and 0–100 cm depths of the Eurasian portion are shown in Table 3, while those for the North American portion are shown in Table 4.

Eurasian Cryosols have somewhat higher SOCC values for both the 0–30 cm and 0–100 cm depths than do North American Cryosols. In addition, the ranges of SOCC values are narrower for the Eurasian Cryosols than for the North American. This is probably because the North American SOCC values are calculated using a much greater number of samples than are the Eurasian values.

Table 2. Area ($\times 10^3$ km^2) of Cryosols in North America and Eurasia.

Soil	North America	Eurasia	Total
Turbic	2587	1285	3872
Static	455	698	1153
Organic	565	2179	2744
Total	3607	4162	7769

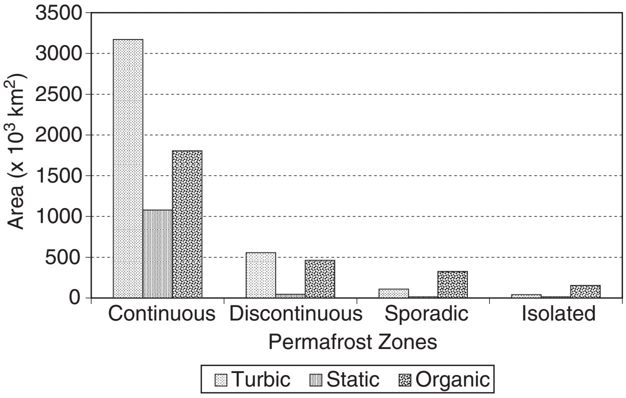

Figure 2. Distribution of Cryosols in the various permafrost zones.

Table 3. Soil organic carbon content (SOCC) for Turbic, Static and Organic Cryosols in Eurasia.

		SOCC(a) (kg m^{-2})**			SOCC(b)(kg m^{-2})**		
Soil	n*	Mean	Min.	Max.	Mean	Min.	Max.
Turbic	20	17.1	4.8	39.1	38.4	17.0	80.3
Static	9	17.1	6.9	31.4	26.0	11.9	49.4
Organic	4	19.5	9.5	33.1	44.3	19.5	63.1

* n – number of pedons (soil profiles).
** SOCC(a), 0 to 30 cm depth; SOCC(b), 0 to 100 cm depth; Min. – minimum, Max. – maximum.

Table 4. Soil organic carbon content (SOCC) of Turbic, Static and Organic Cryosols in North America.

		SOCC(a) (kg m^{-2})**			SOCC (kg m^{-2})**		
Soil	n*	Mean	Min.	Max.	Mean	Min.	Max.
Turbic	211	11.0	0.3	65.0	25.9	0.3	136.6
Static	82	10.4	0.03	34.9	25.6	0.1	65.8
Organic	88	16.9	8.3	67.3	59.2	22.5	133.7

* n – number of pedons (soil profiles).
** SOCC(a) – 0 to 30 cm depth, SOCC(b) – 0 to 100 cm depth; Min.–minimum, Max.–maximum.

3.3 *Organic carbon mass*

The SOCM values of Cryosols in both the North American and Eurasian portions of the northern circumpolar area are presented in Tables 5 and 6 and Figure 5. The Turbic and Organic Cryosols contribute most mass to the SOCM values for the northern circumpolar area at both the 0–30 depth (86%) and the 0–100 cm depth (89%). The distribution of soil organic carbon masses in the various permafrost zones is shown in Figure 3.

Table 5. The soil organic carbon mass (SOCM) at the 0–30 cm depth for Cryosols in North America and Eurasia.

Soil	North America (Gt)	Eurasia (Gt)	Total (Gt)
Turbic	29.0	21.7	50.7
Static	4.7	11.8	16.5
Organic	9.1	42.5	51.6
Total	42.8	76.0	118.8

Table 6. The soil organic carbon mass (SOCM) at the 0–100 cm depth for Cryosols in North America and Eurasia.

Soil	North America (Gt)	Eurasia (Gt)	Total (Gt)
Turbic	63.9	48.1	112.0
Static	11.5	18.1	29.6
Organic	31.2	95.4	126.6
Total	106.7	161.5	268.2

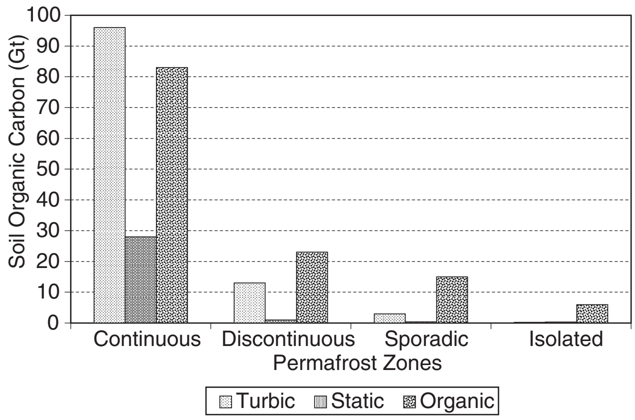

Figure 3. SOCM values of Cryosols in the various permafrost zones.

4 DISCUSSION

Soil organic carbon estimates for Cryosols occurring in northern circumpolar areas were obtained using the recently developed NMLSD spatial database. It was found that these soils cover approximately 7770 $\times$ 10^3 km^2, with approximately 54% of these soils occurring in Eurasia and 46% occurring in North America. Although most of these soils occur in the Continuous Permafrost Zone (78%), they also cover significant areas in the Discontinuous (14%), Sporadic (6%) and Isolated (2%) Permafrost Zones.

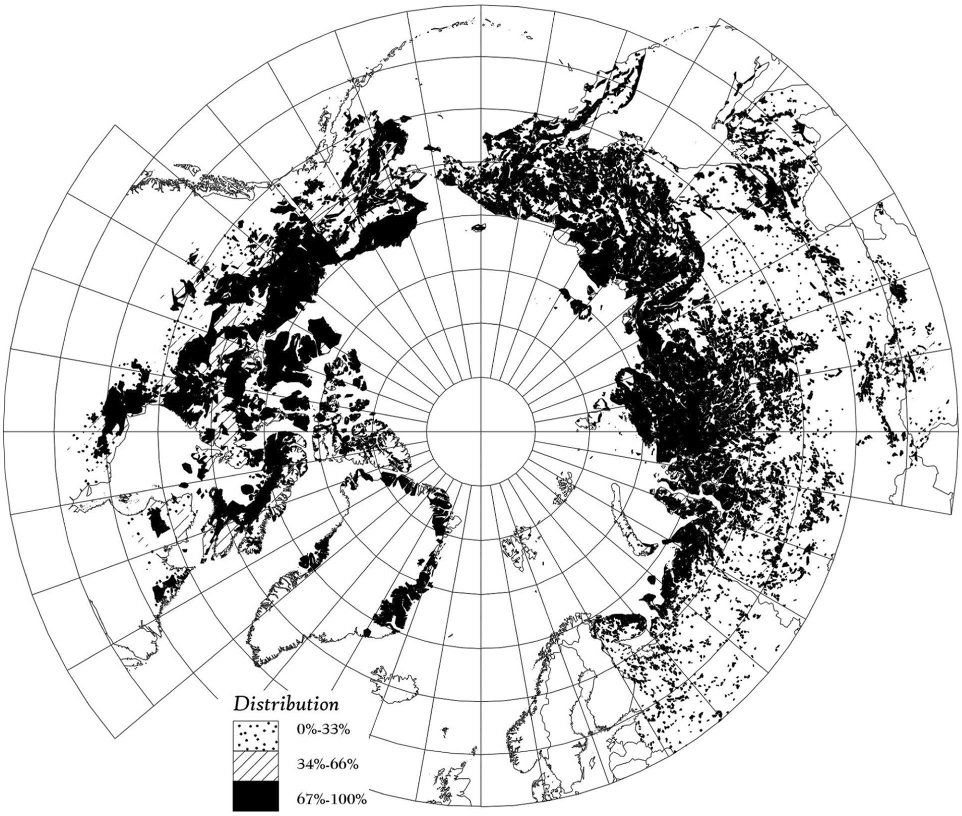

Figure 4. Distribution of Cryosols in the northern circumpolar area.

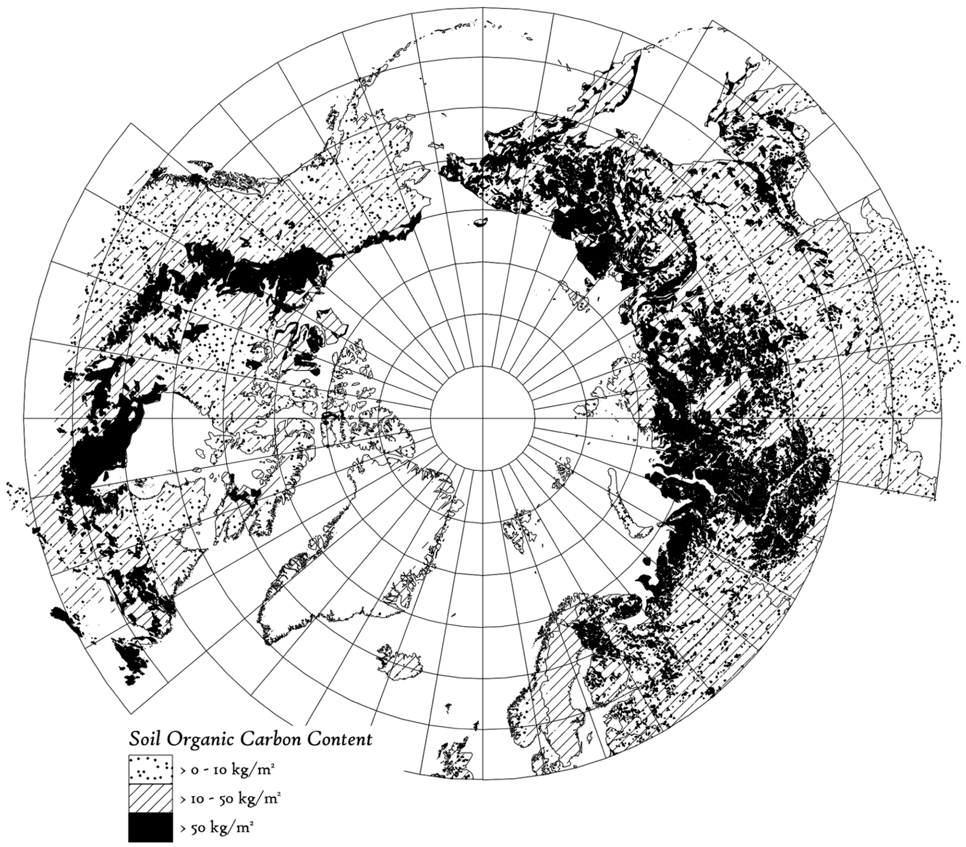

Figure 5. Soil organic carbon content of Cryosols in the northern circumpolar area.

Organic Cryosols have the highest mean soil organic carbon contents at both the 0–30 cm and 0–100 cm depths (Tables 3 and 4). These soils are composed entirely of organic materials with a high concentration of carbon. The second highest mean soil organic carbon contents occur in the Turbic Cryosols, which are mineral Cryosols (Tables 3 and 4). The high values for the Turbic Cryosols are a result of cryoturbation, which moves organic materials from the surface to the deeper soil layers, where the low soil temperatures reduce decomposition.

The northern circumpolar area has soil organic carbon masses of approximately 119 Gt at the 0–30 cm depth and 268 Gt at the 0–100 cm depth. The Eurasian portion of this area contains the greatest soil organic carbon mass (64% of the total at 0–30 cm and 60% at 0–100 cm). These high amounts in Eurasia result in part from the greater Cryosolic cover, but primarily because the SOCM in Eurasia is more than three times that of Organic Cryosols in North America.

It should be pointed out, however, that the carbon estimates presented here relate only to a maximum depth of one metre, but most peat deposits in the northern circumpolar area are greater than one metre deep. In addition, in some areas Turbic Cryosols also contain significant amounts of soil organic carbon below the one metre depth (Tarnocai 2000). This suggests that the amount of organic carbon would be much higher within this area. Therefore, soil organic carbon should be determined to the base of the peat deposit (Organic Cryosols) or, in mineral soils, to a depth of at least two metres. If this were done, the amount (mass) of soil organic carbon at high latitudes would increase, possibly as much as twofold.

The North American soil organic carbon estimates in this paper were generated using data from the Canadian Soil Organic Carbon Database (CSOCD). Bhatti et al. (2002) compared carbon estimates generated by this database with carbon values generated by 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 there was good agreement between the CSOCD- and BFTCS-generated values.

No SOCM data were available for Cryosols in Eurasia. Batjes (1996) provides SOCC values for permafrost-affected organic and mineral soils, but gives no SOCM estimates. Stolbovoi (unpubl.) estimates that all soils in Russia contain 297 Pg of soil organic carbon, but also gives no estimates for Cryosols.

In order to shed some light on the accuracy of the Eurasian soil organic carbon data, the organic soils (Organic Cryosols and unfrozen organic soils) are used as a test to indicate the accuracy since this data is available for Russian peatlands. By definition, organic soils and peatlands are similar since both contain >40 cm of organic material. The areas and soil organic carbon masses of Russian peatlands, estimated by various authors, are presented in Table 7.

Table 7. Areas and organic carbon masses of Russian organic soils or peatlands as estimated by various authors.

Source	Area ($\times 10^3$ km^2)	Carbon mass (Gt)
Stolbovoi (unpubl.)	1162	94
Botch et al. (1995)	1650	215
Efremov et al. (1998)	2730	118

For comparison, this paper estimates an area of 3077×10^3 km^2 and a soil organic carbon mass of 299 Gt for frozen and unfrozen organic soils in Eurasia. It should be noted, however, that a small portion of this area and mass must be attributed to Scandinavia since Eurasia includes this region.

It is evident that the areas and carbon masses estimated by these sources vary widely (1162–2730 $\times$ 10^3 km^2 and 94–215 Gt). These large variations occur because of the poor inventory and limited amount of reliable pedon data available for these soils. This supports the statement of Efremov et al. (1998) that: "The accuracy of estimates of peat carbon is ± 10 to 15 percent for the European part of Russia and ± 20 to 30 percent for the Asian part of the country."

In the northern circumpolar area Cryosols comprise about 16% of the Earth's soil organic carbon pool to a depth of one metre. As shown above, the accuracy of Eurasian estimates, based on the data that is currently available, is low. Because of the high carbon content of northern circumpolar soils and because this area is predicted to be the region most affected by global warming, new data on both the areal extent and carbon content of these soils should be collected if reliable estimates for the soils of the northern circumpolar area are to be obtained.

5 CONCLUSIONS

1. The distribution and organic carbon masses of Cryosols in the northern circumpolar area were determined using the NMLSD database. It was estimated that these soils cover 7769×10^3 km^2 and contain 268 Gt of organic carbon at the 0–100 cm depth.
2. The North American soil organic carbon estimates obtained in this study are similar to estimates made using other methods.
3. The accuracy of the Eurasian soil carbon estimates is low because of the lack of accurate inventory data on the distribution and organic carbon content of the Cryosols.

4 Since Cryosols, which contain about 16% of the Earth's soil organic carbon pool, occur in the area that is predicted to be most affected by global warming, new data is required to improve the accuracy of estimates of the carbon stocks.

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