The Importance of "Deep" Organic Carbon in Permafrost-Affected Soils of Arctic Alaska

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Reporting characteristics for the upper 100 cm of the pedon is common for Gelisols and soil C budgets. The amount of soil organic carbon (SOC) sequestered at a depth of 100 to 200 cm was determined for 29 permafrost-affected soils from northern Alaska. An average of 29 kg C m^{-3} was present within the 100- to 200-cm depth interval, which is contained in the upper permafrost. For a 200-cm-deep profile, about 36% of the SOC pool occurs below 100 cm. From limited data, there were no significant differences in "deep" SOC levels among Histels, Turbels, and Orthels, the three suborders of Gelisols. Based on a previous survey of the Barrow Peninsula, permafrost-affected soils contain 66.5 Tg of SOC in the upper 100 cm, and another 36 Tg in the 100- to 200-cm zone. This C pool is vulnerable to mobilization following warming and increased summer thaw depth in the arctic.

Abbreviations: SOC, soil organic carbon.

PERMAFROST-AFFECTED SOILS (Gelisols) cover 11.2×10^6 km^2 or 8.6% of the world land area (Soil Survey Staff, 1999) and contain an estimated 393 Pg of C in the upper 100 cm. This reservoir constitutes 25% of the global soil organic carbon (SOC) pool (Lal and Kimble, 2000). In the northern hemisphere, Gelisols cover 7.7×10^6 km^2 and contain 268 Pg of SOC in the upper 100 cm of the soil profile (Tarnocai et al., 2003). There is increasing concern that warming observed in the arctic will lead to an increase in the depth of the active layer, or the uppermost soil layer above permafrost that experiences thawing in summer and freezing in winter. Recently, Lawrence and Slater (2005) proposed that by 2100, only 10% of the current 10.5 million km^2 of permafrost is likely to remain within 3.4 m of the ground surface. Although these estimates may be extreme (Burn and Nelson, 2006), there is consensus that the upper permafrost will experience widespread thaw in this century (Anisimov and Nelson, 1997). Jorgenson et al. (2006) documented extensive permafrost degradation and thermokarst formation in arctic Alaska during the past 25 yr. Thawing of the near-surface permafrost could enhance the release of CO_2 and CH_4 into the atmosphere from decomposition of SOC (Waelbroeck et al., 1997). Permafrost-affected soils constitute one of the three most vulnerable sources of SOC to global warming (Intergovernmental Panel on Climate Change, 2007).

Many of the global C budgets express SOC pools to a depth of 100 cm (Schlesinger, 1977; Post et al., 1982). From evidence gathered during the past decade (Michaelson et al., 1996; Bockheim et al., 1998; Tarnocai, 2000), 60% or more of the SOC pool of Gelisols is contained in near-surface permafrost; i.e., from the base of the active layer (i.e., seasonal thaw layer) to a depth of 100 cm. The objectives of this study were to determine the amount of SOC immediately below the standard 100-cm level using deeper excavations and coring in permafrost terrain, and to evaluate the potential impact on the regional C budget.

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STUDY SITES

The data set (Eisner et al., 2004) used in the analysis includes 29 sites from the Arctic Coastal Plain of northern Alaska—26 from near the village of Barrow and three from the Kuparuk River drainage south of Prudhoe Bay (Table 1). All of the sites are within the zone of continuous permafrost. The thickness of the active layer at the study sites ranges from 20 to 73 cm and averages 42 cm.

Current and former drained thaw-lake basins comprise 72% of the Barrow region (Hinkel et al., 2003). Therefore, the sites sampled include primarily drained thaw-lake basins (26 sites) but also alluvial plains (three sites). The vegetation is comprised of wet, nonacidic tundra and moist tundra, typical of the low arctic (Auerbach et al., 1997). The soils are representative of all three suborders in the U.S. system (Soil Survey Staff, 2006), including Histels (11 soils), Turbels (11 soils), and Orthels (seven soils). A soil with abundant SOC in the near-surface permafrost is shown in Fig. 1.

MATERIALS AND METHODS

Soils were excavated using two techniques. Soil pits in the three Kuparuk River Basin sites were dug by hand to the permafrost table in early August when the active layer was at its thickest and additionally excavated to a depth of 100 cm or more with a gasoline-powered Pico impact drill (Bockheim et al., 1998). Detailed soil descriptions were taken at all sites, and bulk samples were collected from each horizon and placed in watertight bags. At the remaining sites, cores were collected in winter when wet, remote thaw-lake basins became accessible to heavy coring equipment transported by snow machine. Cores were taken with a Little Beaver or Big Beaver drill equipped with a 7.5-cm inside diameter SIPRE core barrel. Sampling or coring was done to depths ranging from 120 to 164 cm and averaging 139 cm (Table 1).

Samples were dried at 65°C, and the moisture content and bulk density were determined. Oven-dried samples were ground to pass a 0.5-mm screen, and subsamples were analyzed at the University of Wisconsin using a Dohrmann DC-190 total organic C analyzer (Tekmar-Dohrmann, Mason,

Table 1. Location of sites in Alaska for “deep carbon” study.

Pedon Ref. no.	Latitude	Longitude	Landform	Total depth	Active layer	Soil classification†
	°N	°W		— cm —		
A97–04	69.4866	150.0880	alluvial plain	128	40	Typic Haplorthel
A97–05	69.4880	150.0833	alluvial plain	120	58	Typic Historthel
A97–06	68.7166	149.2000	alluvial plain	125	30	Terric Hemistel
B1–02–01	71.2779	156.4498	drained thaw-lake basin	139	37	Typic Aquiturbel
B1–03–01	71.2779	156.4479	drained thaw-lake basin	135	48	Typic Aquorthel
B2–01–01	71.2725	156.4828	drained thaw-lake basin	122	66	Typic Aquiturbel
B2–02–01	71.2725	156.4762	drained thaw-lake basin	149	42	Typic Aquiturbel
B3–01–01	71.2212	156.4631	drained thaw-lake basin	136	62	Typic Histoturbel
B3–02–01	71.2212	156.4711	drained thaw-lake basin	127	38	Typic Umbriturbel
B3–03–01	71.2212	156.4728	drained thaw-lake basin	128	37	Typic Historthel
B4–01–01	71.2133	156.4796	drained thaw-lake basin	122	44	Typic Aquiturbel
B4–02–01	71.2133	156.4876	drained thaw-lake basin	134	34	Typic Aquiturbel
B4–03–01	71.2133	156.4946	drained thaw-lake basin	135	35	Terric Fibristel
B6–01–01	71.2093	156.5155	drained thaw-lake basin	134	37	Terric Hemistel
B6–02–01	71.2093	156.5208	drained thaw-lake basin	151	73	Terric Hemistel
B6–03–01	71.2093	156.5255	drained thaw-lake basin	148	65	Terric Hemistel
B7–03–01	71.2030	156.5333	drained thaw-lake basin	147	35	Terric Fibristel
B8–03–01	71.2113	156.5361	drained thaw-lake basin	132	38	Terric Hemistel
B9–02–01	71.2170	156.5474	drained thaw-lake basin	143	33	Typic Histoturbel
B10–01–01	71.2608	156.7219	drained thaw-lake basin	160	36	Typic Aquiturbel
B10–02–01	71.2608	156.7261	drained thaw-lake basin	133	23	Terric Hemistel
B10–05–01	71.2608	156.7444	drained thaw-lake basin	132	40	Terric Hemistel
B11–01–01	71.2535	156.6725	drained thaw-lake basin	164	46	Glacic Hemistel
B11–02–01	71.2535	156.6922	drained thaw-lake basin	149	39	Terric Hemistel
B11–03–01	71.2535	156.6809	drained thaw-lake basin	153	34	Typic Aquorthel
B11–04–01	71.2535	156.6881	drained thaw-lake basin	125	51	Typic Aquiturbel
B12–01–01	71.2648	156.6625	drained thaw-lake basin	161	20	Typic Aquiturbel
S1–05–02	71.2793	156.4438	drained thaw-lake basin	151	52	Typic Historthel
S8–05–02	71.2107	156.5353	drained thaw-lake basin	145	33	Typic Aquorthel
Avg.				139	42	
SD				12	13	
Max.				164	73	
Min.				120	20	

† According to Soil Survey Staff (2006).

Fig. 1. Soil organic C concentrated in near-surface permafrost of a drained thaw-lake basin, northern Alaska. The top of the permafrost, which includes the organic-enriched layer, occurs at the top of the shovel blade (note the segregated ice below the organic-enriched layer).

OH). None of the samples reacted with 1 mol L^{-1} HCl and were, therefore, judged to be lacking inorganic C.

The following computations were made. Soil horizon C density was calculated using the following equation:

$$\text{Horizon C density (kg C m}^{-2}\text{ cm}^{-1}) = \text{Bd}_{hor}\ (\text{g cm}^{-3})\%\text{C}_{hor}/10 \quad [1]$$

where Bd_{hor} = bulk density by horizon; $\%C_{hor}$ is SOC for the horizon, and 10 is the unit-conversion factor for reporting horizon C density in kilograms C per square meter per centimeter. Individual calculated horizon C densities were then summed for the active layer and for the 0- to 100-cm layer, and are reported here as kilograms C per square meter. The C density of layers below 100 cm was determined for each horizon or depth interval, summed, and reported as kilograms C per cubic meter. Since none of the pits or cores extended to 200 cm, C density estimates from the limit of coring to 200 cm was from extrapolation of the last horizon, normally a Cgf horizon, to the 200-cm depth. This extrapolation is justifiable in that the Cgf horizon was uniform in composition and typically extended to the base of deeper cores. Differences in active-layer thickness and SOC within the active layer, the 0- to 100-cm layer, and the 100- to 200-cm layer by soil suborder (Orthels, Histels, and Turbels) were tested using analysis of variance and an unpaired *t*-test using Minitab (Minitab Inc., State College, PA).

RESULTS

Based on the traditional approach of reporting data to a depth of 100 cm, SOC density of the 29 study sites ranged from 29 to 73 kg C m^{-3} and averaged 52 kg C m^{-3} (Table 2). Statistical comparisons of bulk density and C content are available in Bockheim et al. (2003). Histels contained the greatest amount of SOC at 56 kg C m^{-3}, followed by Turbels (53 kg C m^{-3}) and Orthels (44 kg C m^{-3}). There were no significant differences in SOC storage, however, among the three suborders. The average value of 52 kg C m^{-3} is similar to the 62 kg C m^{-3} value reported by Michaelson et al. (1996) for total C in the Arctic Coastal Plain of Alaska, although the results are not strictly comparable because most of the samples in the cited study were collected from sites that contain carbonaceous silts of eolian and fluvial origin, which greatly increase the amount of inorganic C. The 56 kg C m^{-3} value for Histels is comparable, however, to the 59 kg total C m^{-3} value reported for equivalent soils (organic Cryosols) in northern Canada (Tarnocai et al., 2003). It is worth noting that the SOC density in arctic wetlands exceeds that found in most life zones except temperate wetlands (Post et al., 1982), despite the fact that near-surface permafrost commonly contains a large amount of segregated ice, including ice wedges, which may "dilute" the amount of SOC in the profile (Bockheim et al., 1999, 2003; Bockheim and Hinkel, 2005).

The active layer contained from 14 to 63 kg C m^{-2}, and averaged 31 kg C m^{-2}. This is comparable to the 27 kg total C m^{-2} value reported for the active layer averaged across 25 sites in arctic Alaska by Michaelson et al. (1996). On average, the active layer contained 58% of the total SOC in the upper 100 cm of the profile, which is nearly equivalent to the 50% value reported by Michaelson et al. (1996).

Soil organic C below 100 cm ranged between 5.0 and 82 kg C m^{-3} and averaged 29 kg C m^{-3} (Table 2). There were no significant differences among suborders: Histels, Orthels, and Turbels averaged 29, 32, and 28 kg C m^{-3}, respectively. These data suggest that, whereas the average profile quantity (to 100 cm) of SOC averaged 52 kg C m^{-2}, a profile extended and extrapolated to a depth of 200 cm would contain 81 kg m^{-2} of SOC. These calculations further suggest that 36% of the SOC in the upper 200 cm would occur below 100 cm.

Table 2. Distribution of soil organic C in Gelisols of arctic Alaska.

Pedon Ref. no.	Active layer	0–100 cm	>100 cm
	kg m^{-2}		kg m^{-3}
A97–04†	19.2	141.0	260
A97–05	32.8	53.9	52
A97–06	14.6	39.8	47
B1–02–01	17.9	38.2	34
B1–03–01	26.0	37.0	29
B2–01–01	38.4	72.8	75
B2–02–01	39.2	68.0	50
B3–01–01	29.8	43.6	12
B3–02–01	36.0	58.6	17
B3–03–01	27.7	49.5	09
B4–01–01	31.5	41.5	40
B4–02–01	29.3	45.4	21
B4–03–01	14.0	36.6	23
B6–01–01	20.5	51.9	17
B6–02–01	62.6	71.2	18
B6–03–01	43.9	49.5	18
B7–03–01	40.5	47.4	15
B8–03–01	29.2	58.0	20
B9–02–01	27.1	42.3	14
B10–01–01	17.5	48.3	30
B10–02–01	32.5	62.5	55
B10–05–01	41.8	64.9	15
B11–01–01	35.3	70.4	38
B11–02–01	33.4	63.2	57
B11–03–01	28.6	63.0	82
B11–04–01	42.9	62.7	7
B12–01–01	33.2	63.9	5
S1–05–02	13.9	34.3	12
S8–05–02	17.1	29.0	11
Avg.	30.6	52.4	29
SD	11.0	12.6	21
Max.	62.6	72.8	82
Min.	13.9	29.0	05
Suborder avg.			
Orthels	24.4 b‡	44.4 b	32 a
Histels	33.5 a	55.9 a	29 a
Turbels	31.2 a	53.2 a	28 a

† Pedon omitted from analysis because of unusually high SOC below active layer.

‡ Differences in lowercase letters within a column indicate statistical difference at $P < 0.05$, based on ANOVA and unpaired t-tests.

DISCUSSION

These findings imply that SOC estimates restricted to the upper 100 cm clearly underestimate the SOC in permafrost-affected soils. To test this idea, we estimated the amount of SOC in the 100- to 200-cm depth interval using the "deep" C densities in Table 2 and areal estimates of broad soil groups on the Barrow Peninsula (Hinkel et al., 2003). These calculations suggest that the 100- to 200-cm depth could contain an additional 36 Tg of SOC (Table 3), compared with the estimated 66.5 Tg for the 0- to 100-cm depth of soils on the Barrow Peninsula. The quality of this estimate is limited, however, because (i) it is based on extrapolation from an average depth of 139 cm to 200 cm, and (ii) only 29 soils are used to represent an area of 1200 km^2. Nevertheless, the analysis demonstrates the importance of SOC below the 100-cm depth. For example, in 3-m-deep Turbels from the Mackenzie

Table 3. Estimation of organic C density by depth in soils of the Barrow Peninsula.

Basin classification	Area†	Avg. C density		Total soil organic C		
		0–100 cm	100–200 cm	0–100 cm	100–200 cm	0–200 cm
	km^2	kg m^2		Tg		
Basins	792	52.4	29	41.5	23.0	64.5
Non-basins	435	57.5	30	25.0	13.1	38.1
Total	1227			66.5	36.0	102.5

† From Hinkel et al. (2003).

River Valley in Canada, 34% of the total SOC mass occurred in the 100- to 200-cm depth and 11% in the 200- to 300-cm depth (Tarnocai, 2000).

A major concern is what proportion of the SOC in near-surface permafrost could become oxidized during arctic warming to produce C-based greenhouse gases and strengthen feedback. It is unlikely, however, that this SOC will become a source of CO_2 in a warming scenario for the following reasons. Although continued warming of the arctic will increase the thaw depth and expose C-rich materials in the near-surface permafrost, the cold temperatures at this depth may limit or preclude microbial decomposition and release of CO_2 to the atmosphere. Moreover, an increase in soil cryoturbation induced by soil warming may redistribute biologically active forms of C to the subsoil, enabling it to be preserved for thousands of years (Bockheim, 2007).

CONCLUSIONS

The current approach of reporting SOC density for the upper meter of soil ignores processes that accumulate deep soil C in periglacial regions and systematically underestimates the total amount in Gelisols of the northern hemisphere. In permafrost-affected soils of arctic Alaska, there was an average of 29 kg C m^{-3} of SOC within the 100- to 200-cm depth interval. Based on an analysis of 29 pedons, about 36% of the SOC pool occurs between 100 and 200 cm. There were no significant differences in "deep" SOC levels among the Histels, Turbels, and Orthels, the three suborders of Gelisols. Based on the soils database for the Barrow Peninsula, the soil from 100 to 200 cm could contain 36 Tg of SOC, compared with the estimated 66.5 Tg for the 0- to 100-cm depth.

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