High stocks of soil organic carbon in North American Arctic region

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ABSTRACT

The Arctic soil organic carbon (SOC) pool is important but poorly defined. The most cited pool size estimates are based on one study that uses 48 North American soils of which only 5 are actually in the Arctic[1]. Three of these 5 are in the colder high arctic not representative of soils across Arctic North America. Soil map-based pool estimates[2] rely on subarctic soils to project the Arctic. In all of these studies soil

sampling to depth and direct measurements are lacking. We studied 139 soils from different landscape units of the North American Arctic to a 1 meter depth and found SOC stores in mountains, glacier-scoured rubbleland, hilly upland, and lowland to average 3.8, 3.4, 40.6, and 55.1kgSOCm^{-2} respectively. When projecting our data to the North American Arctic based on the landscape units we found a pool size of 98.2 Gt with a higher average SOC store of 34.8kgSOCm^{-2} compared to the previous estimate of 21.8kgSOCm^{-2} from a life-zone based study[1]. We also detail SOC spatial distribution with depth that has not previously been available but will be important for climate warming studies.

The Arctic occupies about 13% of the land area and is estimated to hold about 14% of the soil organic carbon pool (SOC)[1]. This widely cited estimate is from the 1982 study of SOC in the world's life zones[1] and is for the entire tundra life zone but is commonly cited for the estimation of Arctic SOC pools. In this study the tundra regions were represented by an average value of 21.8 kg m^{-2} SOC for an area of 8.8x10^{12}m^{2}. A comparison of the 48 tundra data points used in the Post et al. study[1] with the current Circumpolar Arctic Vegetation Map (CAVM)[2] reveals that only 5 of the 48 points for the North American tundra are in the Arctic as defined by the CAVM (area: 5.05x10^{12}m^{2}, defined as treeless arctic area). Three of those five points are in the High Arctic at one location. However the CAVM study revealed strong a bioclimatic gradient in the Arctic with large increases in biomass production (organic carbon) on soils from the High Arctic to the Low Arctic. Other frequently cited studies of Arctic tundra soils find values ranging from 20 kg m^{-2} to

29 kg m^{-2} SOC[3,4,5,6] and include either only the upper 20 to 40cm of soil or values estimated to100 cm. All of these studies rely heavily on the use of data to less than 1 meter depth and estimated bulk density (BD) values. The Chapin et al.[3] and Oechel studies[4] used only one Alaska site with limited depth and the Stolbovoi study[5] of Russian Arctic SOC used estimated BD, depth and SOC contents. Tarnocai et al [2] measured SOC stored in soils of Arctic Canada mostly using points estimated to a meter depth and using drill cores from one area for projecting bulk density and SOC measurements for other areas. These studies having offered the only available data are of necessity cited repeatedly in the literature even though soils of the Arctic were known to contain considerable carbon at depths up to a meter or more due to cryoturbation[6,7].

Patterned ground features, caused by frost cracking and heave, are prominent on the circum-arctic landscape[8,9]. These features include sorted and nonsorted circles, stripes, desiccation polygons and ice wedge polygons[8]. Associated with these features arctic tundra soils show strong evidence of cryoturbation that is characterized by warped, broken and distorted soil horizons and surface organic matter being churned down to the lower active layers and upper permafrost[7,10]. Recently, there have been many studies assessing SOC in relation to global change, studies such as SOC temperature sensitivity[11], global SOC distrubution[12] and carbon emission stabilization assessments[14]. These regional and global SOC assessments all must continue to use the average value of 21.8 kg m^{-2} for Arctic SOC stores, an estimate that ignores a significant part of the cryoturbated SOC[10]. However, current studies in the Arctic have pointed to the importance of this deeper soil profile OC and its potential for effecting and being affected by climate change[14,15]. There are several lines of evidence pointing to the importance of these SOC-stores as they are affected by warming temperatures such as the wide-spread warming of the upper permafrost in the Arctic[16,17]and efflux of up to 80% of the seasonal C-flux from tundra soils during the cold-season when the OC rich subsoils are the warmest of the soil profile[14,15].

Our study takes a systematic approach to examine and assess the SOC pools of arctic soils in order to minimize the uncertainties in both SOC profile depth and regional distribution that is associated with previously data. First we selected North American study sites from different landscape units of the Circumpolar Arctic Vegetation Map (CAVM)[18] (Figure 1). Secondly, we examined soils across the complete cycle of pattern ground expression to a 1 meter or more depth at each site using the state of the art techniques to describe and sample the cryoturbated soil profiles including direct measurement of soil bulk density, moisture/ice content, and thicknesses of warped (cryoturbated) horizon profiles[19,20]. Thirdly, we incorporated published Canadian data that was obtained using comparable methods[7]. Our objective in the employment of these three quality-control components in data collection is to give North American Arctic SOC store estimates that are for the first time based on measured data points all from the Arctic representing soils to depths that are likely to be affected by climate change. We do this for a defined Arctic region (treeless Arctic)[18] a region with the best current information on vegetative cover communities.

RESULTS AND DISCUSSION

SOC depth distribution

The presence, form and abundance of patterned ground plays a key role in determining tundra vegetation[21,22], the morphology and properties of cryogenic soils[10,23] and the dynamics and sequestration of carbon[9,24,25]. In the Arctic much of the movement of SOC from the surface to depth is accomplished through cryoturbation[25]. This movement is caused by cracking due to soil freeze-thaw cycles and by soil hydrothermal gradients that produce differential frost heave[26]. Nonsorted circles are a common form of patterned ground in the hilly uplands and lowlands of the Middle and Low Arctic while polygonal cracking and striping patterns are common in the hilly uplands of the High Arctic[21,23]. Although based on surface observations, the influence of nonsorted circles appears to decrease from the north to south we found nonsorted circles were also common in the hilly uplands and lowlands of the Low Arctic, but with their surface appearance masked by vegetation. The SOC in a typical soil profile under a nonsorted circle is unevenly mixed and distributed in recognizable masses (cryotubated soil horizons, see supplementary figure) within the active layer and upper permafrost[7,10]. Chunks of surface organic matter, even whole-plant tussocks, were found subducted along the bowl-shaped depressions of the permafrost table surface under nonsorted circles. Our research indicates that most cryoturbated SOC occurs within the depths of 60–100 cm on hilly upland and 80-120 cm in lowland tundra, 83% and 73% respectively of SOC in the subsurface active layer and permafrost combined (Table 1 and supplementary data set). The reason seems to be that the subduction of surface generated SOC goes to the top of the contemporary permafrost table and over the century time-scale the top of the permafrost can fluctuate on the order of tens of centimeters and sequester subducted SOC.

We found average SOC stocks for landscape units varied widely across the Arctic (Table 1), Lowland and upland landscape soils contain higher SOC stores of on average over 10 times those of rubble and mountain soils. Although the range of SOC stores overlapped for the lowland and upland sites, the lowlands tended to average the highest with a larger percentage of their stores in the permafrost than the upland sites, 47% and 37% respectively. However, the upland landscape had on average greater SOC stores in the subsurface active layer, 45% of SOC compared to 26% in lowlands. These distribution patterns are consistent with what could be expected with different landscape processes affecting SOC accumulation. Lowlands tend to be wet and build up organic layers with relatively limited mixing but permafrost table moving up over time to include layers of organics. Uplands on the other hand must accumulate organics that are in turn subject to erosion and slope processes each respectively removing and mixing organic layers from and into the active layer. The climate gradient across the Arctic has a strong effect on the biologically-dependant accumulation of SOC. This can be seen when the data are grouped by bioclimatic subzones[18] within landscape types (lowland and upland, Figure 2). Lowland and upland units contained highest stores but the SOC stores for the High Arctic subzones (A and B) sites were distinctly lower than for the Low Arctic (subzones D-E) sites. However each landscape unit exhibited a different pattern in SOC moving from north to south (subzones C to E). While upland SOC increased with warmer bioclimatic subzone, lowland SOC was highest in subzone C and decreased in the south. This is due to the combination of high accumulation on the wetter lowland surfaces and permafrost preservation of cryoturbated SOC in lower layers (Table 1). The upland SOC pattern follows that of increased surface biomass production that follows increases in annual temperatures[21] and increased cryoturbation preservation (permafrost stores) of SOC moving southward through the Arctic. We found overall average Arctic SOC stores based on soil area (Table 1) to be 34.8 kgSOC m^{-2} that is higher than reported by previous investigations[1,2,3,4] that range from 20 to 29 kgSOC m^{-2}. We attribute this largely to the measurement method differences mentioned earlier including actual measurement of SOC to 1 meter depth (into the permafrost) and use of only soils data points actually from the arctic region. This is in contrast with previous methods that included the estimation of deeper SOC and translation of soil data and soil classification units from the subarctic over to the Arctic. Dependence on Subarctic SOC stores for estimating Arctic stores could be expected to lower overall estimates due to the lower stocks in soils there relative to the Arctic region[1,27]. Estimation of permafrost stores using subarctic profiles could have the same effect as cryoturbation is less in the subarctic with more surface vegetation for insulation causing reduced influence of cryoturbation[21,27]. The average SOC store estimate for the active layer alone is 21.7 kgOC m^{-2} (Table 1) an amount closer to the previous estimates for whole soil to 1 meter (21.8 and 28.5 kgOC m^{-2})[1,2] . There is a strong gradient effect of latitude on climate and hence biology and biotically-fixed carbon (biomass production) across the Arctic[21]. That effect can be seen when SOC data is averaged by bioclimatic subzones[18] within landscape units (Figure 2). It is likely that this effect environmental gradient is responsible for the wide range of SOC stock values observed for landscape unit averages (Table 1). A similar or even greater gradient could be expected for averages by soil classification units[2] across the combined Arctic and Subarctic.

SOC pools of the North American Arctic

We assigned measured Arctic SOC data to the CAVM landscape units[18] they represent, averaged them by unit (data in Table 1) and projected SOC pool size using the area of the North American Arctic (Canada plus the U.S.) from CAVM[18] (Table 2). We estimate the North American Arctic SOC pool size to be 98.2 Gt, with 19.2, 42.1 and 36.9 Gt in the surface organic enriched layer, the subsurface active-layer and the permafrost respectively. The only other previous comparable published estimate that found in the literature is considerably lower at 43 Gt SOC for the Canadian treeless Arctic[2]. Excluding the U.S Arctic portion in our estimate, our Canadian Arctic pool estimate would be 76 Gt SOC (of the 98 Gt total North American pool) a value over 75% higher. Again the higher ground stock estimates in Table 1 are responsible for this increase, and we attribute that largely to the use of measured soils to 1 meter and the use of only Arctic soils as opposed to use of projected depth data and subarctic study sites in the previous estimate.

The distribution of the Arctic SOC pool with regard to the surface, active layer and permafrost has not been evaluated before but is very relevant in assessing changes that will occur across the Arctic system[14]. Were SOC is located in the soil profile is especially relevant and useful to climate warming assessments that need to evaluate effects on separate soil processes that vary with temperature and depth throughout the whole annual cycle of seasons[14]. In lieu of any additional Arctic data, our estimates are based on the best available to date. The range and standard deviation of SOC data for each subzone given in Table 1 can provide an idea of the variability found for the landscapes and deviations are similar to those found by others[1,2]. As presented in Figure 2 our data may be reassessed in different ways to account for Arctic climate gradation and the similar gradations in climate change that may occur. In light of recent studies emphasizing the importance of deeper carbon and the whole season carbon dynamics, we provide the first all-points-measured data based estimate for deeper profile SOC stocks across Arctic North America. It seems that there is a similar lack of to-depth measured Arctic soil data points for the Eurasian Arctic[5] and estimates there are as could be expected, similar in magnitude to the Canadian data[2]. Eurasian estimates are derived in a similar method to the Canadian ones, from soil class unit averages of largely Subarctic with a few Arctic data points. They also are mainly estimated to depth using Subarctic data to generalize for the region. It has been shown that warming trends for the permafrost are similar in Eurasia and North America but that there are differences in the magnitude of warming between the Subarctic and Arctic regions[16,17], yet the available pool estimates are averaging Arctic and Subarctic with data largely projected and from the Subarctic. There are strong similarities in circumarctic vegetation[9,18], landscapes and landform[28] and soil forming factors[29]. With these known similarities it is reasonable to assume that in the future more systematic investigation of circumarctic soils will also find SOC stores higher than current estimates and similar to those we found for the North American Arctic. Such a wide difference in range of estimates combined with the recently recognized importance of deeper SOC in C-flux from tundra under changing climate should be incentive to better delineate the SOC stocks of the entire circumarctic region.

METHODS

In this study a total of 117 soils pits were excavated from the Seward Penninsula, Alaska in the west and foothills of the Brooks Range to the Archipelago of the Canadian Arctic between 1993 and 2006. Soil organic carbon data were included from 22 Arctic Canada sites[7] across the eastern-central Arctic, data points obtained with similar data collection methods for a total of 139 study soils. The carbon stocks were calculated based on soils profile excavated across the whole cycle of predominate surface patterns where present (such as from the center of a nonsorted circle to the area in between the circles, or inter-circle). Excavations were to a meter depth and SOC expressed as $\mathrm{kgOCm^{-2}}$. For soils with highly cryoturbated, broken and warped horizons, thicknesses were calculated by the relative proportion of each horizon in an exposed meter square profile and for all soil horizons soil bulk density (block, core or clods samples) and organic carbon content were measured[19]. Sampling sites were selected to cover all the landscape units in the Arctic North America; lowlands (plain), uplands (hilly), rubblelands (including glacial-scoured bedrock), and mountains according to CAVM[2]. The OC stocks of 0 $\mathrm{kgSOC\ m^{-2}}$ were assigned for areas covered by lakes, glaciers and ice fields. Soil ice and rock fragment contents measured were used to correct volumetric measurements. The boundary of the upper permafrost was identified by cryogenic and ice structures[30]. Soil organic carbon was measured on samples treated with HCl to remove inorganic carbon then determined on LECO CHN analyzer.

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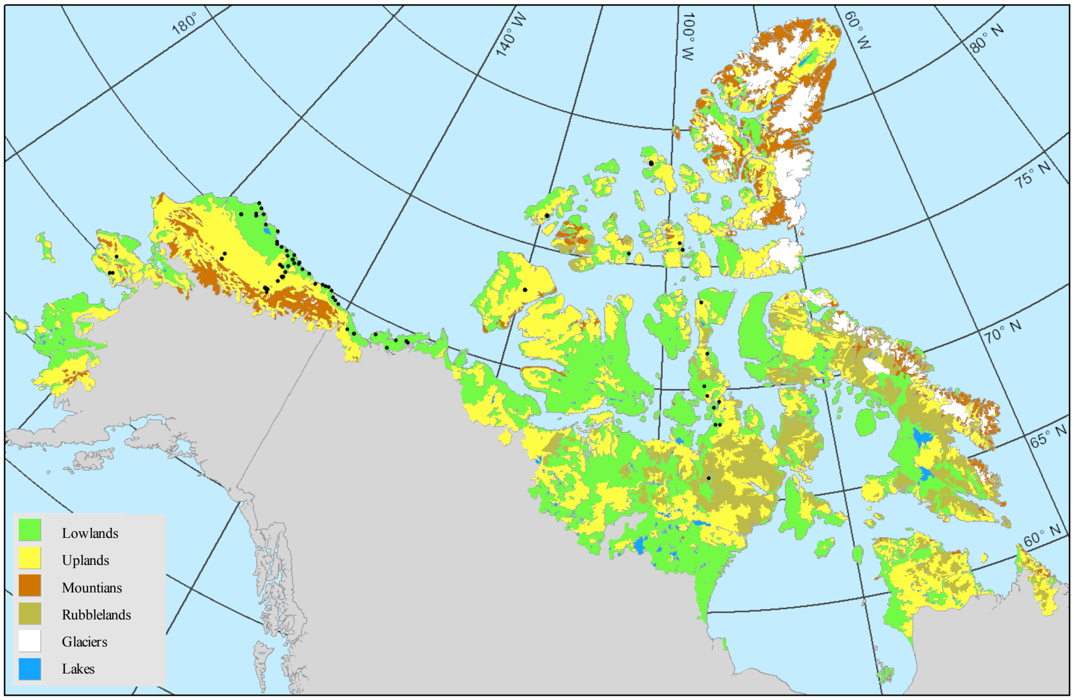
AKNOWLEDGEMENTS

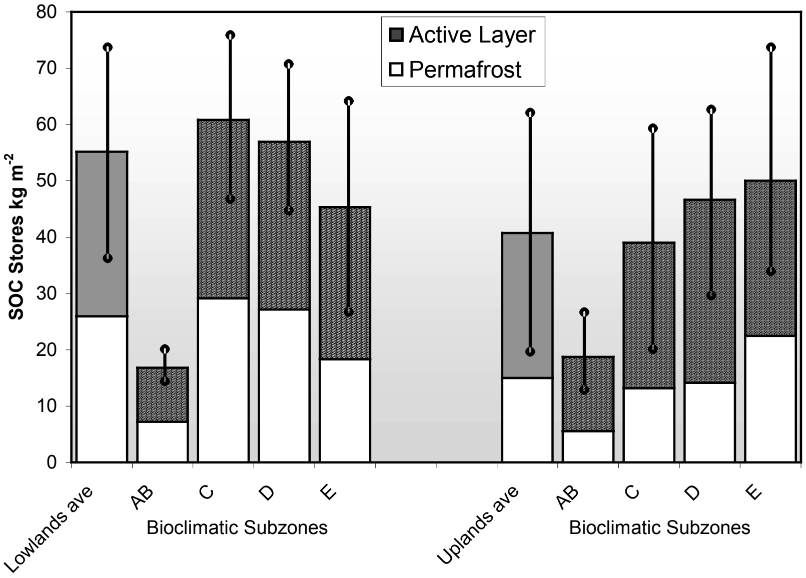
The following National Science Foundation projects contributed to this work: Arctic Transitions in the Land-Atmosphere System, the Flux Study, Biocomplexity of the Arctic System, and Arctic Coastal Transfer. Also significant contributions from the U.S Dept. of Agric. Hatch Project and Global Change Initiative, and Hilmar Maier for help with mapping data.

Figure 1 Study site locations. Colors are landscape units derived from CAVM[18] some points represent several soil study sites.

Figure 2 The effect of Arctic latitudinal climate gradient on landscape stores of SOC. The two higher SOC stores landscape units from table one are displayed, with landscape units data averages by Bioclimatic subzone[18] and display of one standard deviation unit above and below the mean.


180°
140° W
100° W
60° W
80° N
75° N
70° N
65° N
60° N
Lowlands
Uplands
Mountians
Rubblelands
Glaciers
Lakes


Lakes



80
70
60
50
40
30
20
10
0
SOC Stores kg m-2
Active Layer
Permafrost
Lowlands ave
AB
C
D
E
Bioclimatic Subzones
Uplands ave
AB
C
D
E
Bioclimatic Subzones

Table 1. Average SOC stores for the landscape units[18] of the North American Arctic. Data set is given in supplementary information.

Landscape Unit[1]	n[2]	Active Layer		Permafrost	Total
		Organic Enriched Surface Horizons	Subsurface Horizons (To Permafrost)	Upper Permafrost To 1 Meter Depth	To 1 Meter
		kg SOC m⁻²			
Lowlands	54	15.1	14.1	25.9	55.1
Std(range)		*14.5(2.1-51.9)*	*12.9(0-47.8)*	*15.8(1.5-68.1)*	*18.9(14.3-95.0)*
% of total		27	26	47	
Uplands	76	7.5	18.2	15.0	40.6
Std(range)		*11.6(0.1-63.5)*	*13.1(0-57.6)*	*13.6(0-53.0)*	*22.7(6.0-104.3)*
% of total		18	45	37	
Rubblelands	5	0.8	2.1	0.5	3.4
Std(range)		*2.1(0.1-3.7)*	*2.8(0.1-6.6)*	*1.1(0-2.4)*	*3.5(0.3-9.0)*
% of total		23	62	15	
Mountains	4	0.7	3.1	0.0	3.8
Std(range)		*0.5(0-1.3)*	*1.6(1.6-5.3)*	*(0)*	*1.8(1.6-6.1)*
% of total		18	82	0	
Ave wtd[3]		*6.8*	*14.9*	*13.1*	*34.8*
% of total		20	42	38	

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[1] Lowlands were soils in CAVM units W1-3, Uplands were in units B1, G1-4, P1-2 and S1-2, Rubbleland soils were in units B2, and Mountains were in units B3-4 [18].

[2] n=number of soil profiles averaged for the landscape unit.

[3] averaged using relative areas of each landscape unit in N. American Arctic[18]

Table 2. Summary of SOC pool estimates to 1 meter depth for the North American Arctic (Canada and U.S.A.) by landscape units and respective map areas derived from CAVM[18].

Landscape Unit[1]	Map Area[2] N.Amer. (km^2x10^3)	Active Layer: Organic Enriched Surface Horizons	Active Layer: Subsurface Horizons (To Permafrost)	Permafrost: Upper Permafrost To 1 Meter Depth	Total: To 1 Meter
		Gt SOC			
Lowlands	220	3.3	3.1	5.7	**12.1**
Uplands	2067	15.5	37.7	31.0	**84.2**
Rubblelands	371	0.3	0.8	0.2	**1.3**
Mountains	161	0.1	0.5	0	**0.6**
(Sub Total)	(2819)				
Glaciers	170	-	-	-	-
Lakes	51	-	-	-	-
TOTAL	3040	**19.2**	**42.1**	**36.9**	**98.2**
% of Total		19.6	42.9	37.5	

[1] Lowlands were soils in CAVM[18] units W1-3, Uplands were in units B1, G1-4, P1-2 and S1-2, Rubbleland soils were in units B2, and Mountains were in units B3-4.

[2] Taken from CAVM[18].