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The Distribution of Soil Carbon and Nitrogen Stocks Among Dominant Geomorphological Terrain Units in Qarlikturvik Valley, Bylot Island, Arctic Canada

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Key Points:

- Geomorphological terrain units differ in soil carbon and nitrogen stocks and should be considered in Arctic soil inventories
- Humid low-center ice-wedge polygons store larger quantities of soil carbon and nitrogen than mesic flat ice-wedge polygons and alluvial fans
- Alluvial fans are widespread features of Arctic landscapes and store significant quantities of soil carbon and nitrogen

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Soils of circumpolar regions store large amounts of carbon (C) and are a crucial part of the global C cycle. Yet, little is known about the distribution of soil C stocks among geomorphological terrain units of glacial valleys in the Arctic. Soil C and nitrogen (N) content for the top 100 cm of the dominant vegetated geomorphological terrain units (i.e., alluvial fans, humid polygons, mesic polygons) at Qarlikturvik Valley, Bylot Island, Canada have been analyzed. Soil C content was greatest in humid low-center ice-wedge polygons (82 kg m^{-2}), followed by mesic flat-center ice-wedge polygons (40 kg m^{-2}), and alluvial fan area (16 kg m^{-2}), due to prevailing geomorphological processes, differences in vegetation and soil characteristics, as well as permafrost processes. Soil N content was greatest in humid polygons (4 kg m^{-2}), followed by mesic polygons (2 kg m^{-2}), and alluvial fan area (1 kg m^{-2}). Vertically, C and N decreased with increasing depth except for a peak in C at depth in humid polygons, a likely result of past changes in vegetation cover. At Qarlikturvik Valley, which has a size of 121.7 km^2, alluvial fans store 0.226 Tg organic C and humid and mesic polygons store 1.643 and 0.218 Tg organic C, respectively in the top 100 cm of soil. Findings like these are important to further constrain pan-Arctic soil C and N stock estimates and thus climate models.

Plain Language Summary Permafrost soils of the Arctic store large amounts of carbon (C) and nitrogen (N), which may be emitted to the atmosphere in form of greenhouse gases further enhancing global warming when thawed under warmer conditions. It is therefore important to know how much C and N these soils store. Various approaches have been used for upscaling in the past. Here, soil C and N stocks were estimated for the main vegetated geomorphological terrain units of a valley in the Arctic. Soil C and N levels varied among geomorphological units, due to prevailing geomorphological processes, differences in vegetation and soil characteristics, as well as permafrost processes. Overall, C and N decreased with increasing depth. These data will allow us to better constrain soil C and N stocks of permafrost regions and ultimately climate models.

1. Introduction

Arctic regions store vast amounts of carbon (C) in their soils and are a crucial part of the global C cycle (e.g., MacDougall et al., 2012; McGuire et al., 2018; Zimov et al., 2006). These C deposits are brought about by low temperatures, waterlogging, and cryoturbation, preventing the decomposition of organic matter (OM) and facilitating long-term C storage (Davidson & Janssens, 2006). Permafrost regions are sensitive to warming, as indicated by rising soil temperatures, thawing permafrost, and increasing active layer thickness (Biskaborn et al., 2019). Consequently, long-term soil C sinks may become sources, as the decomposition of soil OM and associated increases in microbial respiration are expected to represent a strong positive feedback to global warming (Elberling et al., 2013; Schädel et al., 2014; Y. Wang et al., 2020). Similarly, nitrogen (N) stored within these soils may be transformed via denitrification or nitrification into nitrous oxide (N_2O), another potent greenhouse gas (Hugelius et al., 2020; Remde & Conrad, 1991; Salmon et al., 2018). Uncertainties arise, limiting the use of current soil C inventories of Arctic regions for global climate projections, due to our limited understanding of the size of the soil C and N stocks and the factors that influence them (Hugelius et al., 2014; Opfergelt, 2020; Palmtag et al., 2018).

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Early attempts to quantify soil organic carbon (SOC) stocks at a pan-Arctic scale suggested 1,700 Pg C are stored in the upper 3 m of soils of the northern permafrost region (Tarnocai et al., 2009). As more data became available this estimate has been constrained to 1,300 Pg C (Hugelius et al., 2014). A more recent estimate suggests global permafrost regions store 1,568 Pg C (Strauss et al., 2021). No such estimate exists for soil N stocks despite their importance in SOC cycling, as N availability influences plant productivity, thus soil OM inputs, and constrains the decomposition of soil OM (Mack et al., 2004). Most studies that assessed regional soil C stocks extrapolated data from soil pedons based on landforms (e.g., Ping et al., 2008; Zubrzycki et al., 2013), soil type (e.g., Hugelius et al., 2013), vegetation classes (e.g., Hugelius & Kuhry, 2009; Siewert et al., 2015), or a combination thereof (e.g., Hugelius, 2012; Hugelius et al., 2014; Siewert et al., 2016), as these factors have a major influence on SOC stocks (Grosse et al., 2011). Moreover, they can be readily determined based on existing soil and vegetation maps and/or satellite imagery, especially for lowlands (Weiss et al., 2017). However, SOC stocks in mountainous and sloping terrains, which are widely distributed and cover about 13% of the area without any ice cover in the Arctic (Walker et al., 2005), are poorly represented in these assessments and are thus associated with large uncertainties (Hugelius et al., 2014).

Geomorphological processes are particularly important in the formation of soil C stocks in mountainous terrain and associated sloping foothills, as they periodically redistribute and burry soil OM (Hugelius et al., 2014; Weiss et al., 2017). Since alluvial fans form at the bottom of cliffs and slopes they are very common terrain features of Arctic regions (French, 2017). Indeed, in Zackenberg Valley, Greenland alluvial fans occupy an area of about 12%–15% (Cable et al., 2018; Palmtag et al., 2018). In alluvial fans, discharge travels downslope either as concentrated or sheet flow. Sufficiently concentrated flow may result in debris flow, while sheet flow may result in thin layers of deposited sediment (Blair & McPherson, 1994). Although little is known about the biogeochemistry of sediment deposited in alluvial fans, soil C contents in alluvial fans ranged from 0.4% to 19.6% in Zackenberg Valley, Greenland (Cable et al., 2018). Given the widespread distribution of alluvial fans in Arctic landscapes, research on the biogeochemistry of C and N stocks in alluvial fans and how it compares to other terrain units is urgently needed.

Qarlikturvik Valley at Bylot Island is a typical geosystem of the Eastern Canadian Arctic. In addition to incised plateaus with alluvial fans at the hill toes, terraces with polygons can be found along the proglacial river. These tundra polygons are the result of repeated frost cracking of the ground in winter and water entering these cracks during snow melt, leading to the formation of ice veins and eventually ice wedges (Allard, 1996; Fortier & Allard, 2004, 2005; Fortier et al., 2006). Accretion of organic material and eolian sediment leads to the formation of soil C deposits (Allard, 1996; Ping et al., 2016). Permafrost aggrades either downward after the accumulation of peat/sediments (epigenetic permafrost) or upward concurrent with peat/sediment deposition (syngenetic permafrost). The later thus freezes shortly after deposition potentially sequestering large quantities of C (Ewing et al., 2015). Low-centered polygons often accumulate water and are therefore considered humid polygons. They form syngenetic permafrost. While low-centered polygon rims and gently sloping terrain are drier and considered mesic environments (Perreault et al., 2016), form epigenetic permafrost. These differences in permafrost formation and soil moisture likely influence soil C stocks (Ewing et al., 2015; Lee et al., 2012; Zona et al., 2012). However, in the Kolyma Delta, Siberia soil C stocks were very similar in the active layer of the polygon ridge (i.e., mesic conditions) and the polygon center (i.e., humid conditions), but greater in the frozen ground of the polygon center. In contrast, in the Lena Delta active layer soil C was greater at the polygon center, but frozen ground soil C was greater at the polygon ridge (Beermann et al., 2016). This suggests that soil C and N stocks of polygonal terrain are also highly variable, warranting further data to constrain uncertainties associated with current soil C inventories.

This study aimed to assess soil C and N stocks at Qarlikturvik Valley at Bylot Island, Nunavut, Canada and to explore potential differences in soil C and N concentrations among dominant vegetated geomorphological terrain units (i.e., alluvial fans, humid polygonal terrain, mesic polygonal terrain) and with depth. It was hypothesized that C and N stocks differ among geomorphological terrain units, as the factors that determine C and N inputs, storage, and losses also differ among these terrain units.

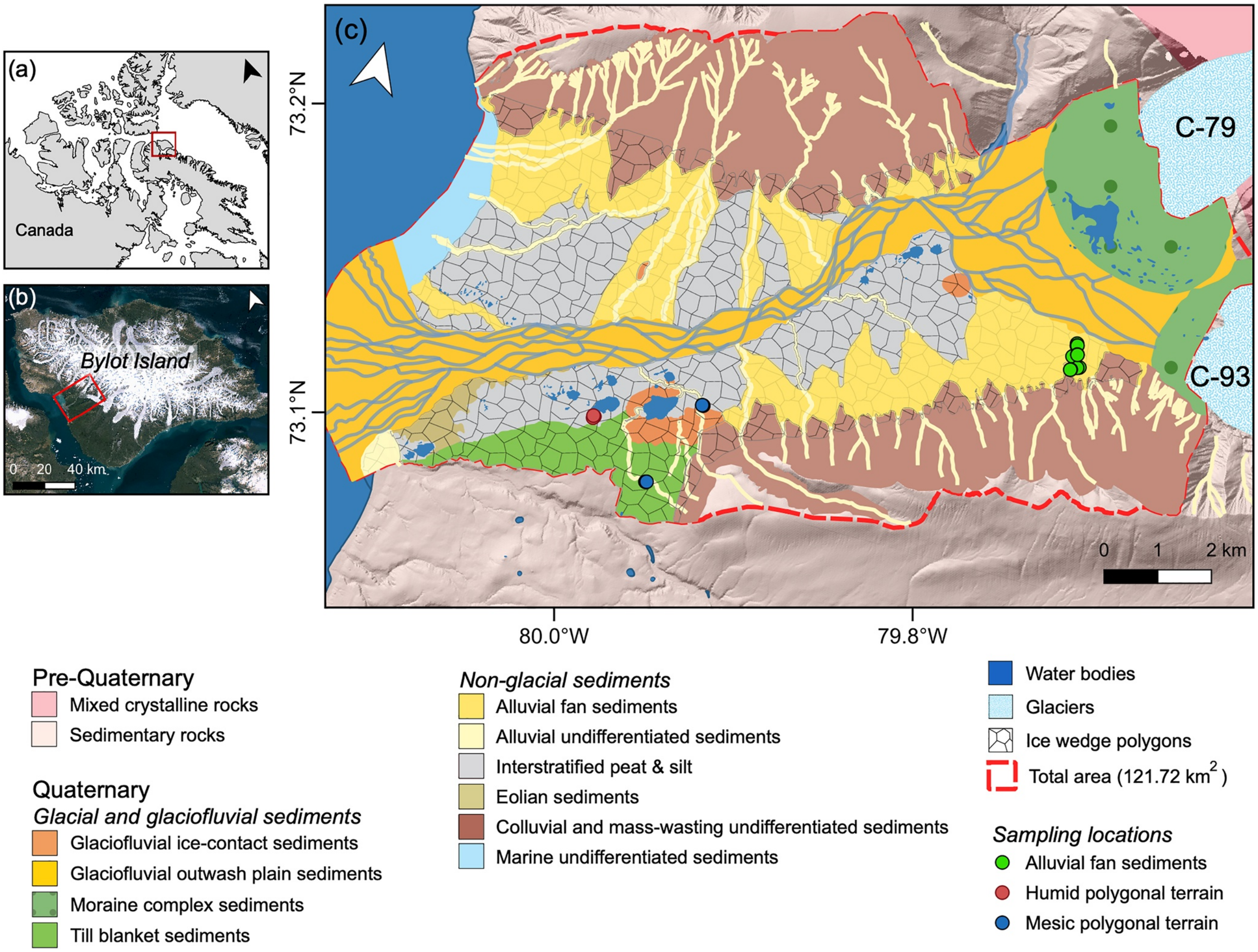


Figure 1. (a) Location of Bylot Island in the Eastern Canadian Arctic, (b) the location of Qarlikturvik Valley on Bylot Island, and (c) the locations of the soil pedons sampled at Qarlikturvik Valley (73°10′N, 80°00′W), where green points represent alluvial fan sampling locations, blue points: mesic polygons, and red points: humid polygons (based on Coulombe et al. 2021).

2. Materials and Methods

2.1. Study Site

Qarlikturvik Valley (73°10′N, 80°00′W, Figure 1) is located on the southern plain of Bylot Island, Nunavut, in the eastern Canadian Arctic. The valley floor has a length of approximately 17 km with a width of up to 4 km (Godin & Fortier, 2012). It is bounded by the glaciers C-79 and C-93 to the East, and plateaus and terraces comprising up to 4–5 m of ice-rich peat mixed with eolian sediment to the North and South. Alluvial fans at the toe of incised plateaus are made of silty sand and gravels, covered by organics except in the numerous active channels. Streams and rills from sub-perpendicular gullies and alluvial fans flow in a proglacial braided river, forming a glaciofluvial outwash plain. The south-western portion of the valley is dominated by glacial deposits covered by organics (Fortier & Allard, 2004). Approximately 17.6 km^2 of Qarlikturvik Valley are covered by alluvial fans, 20.2 km^2 by humid polygonal terrain, and 5.5 km^2 by mesic polygonal terrain. This corresponds to 14.5%, 16.4%, and 3.5% of the total area, respectively (Figure 1). The remaining area is covered for example, by colluvium (30.1%), the glacio-fluvial outwash plain (18.8%), glacio-proximal terrain (moraine, 7.7%), and bedrock outcrops (4.1%) (Figure 1).

The annual mean air temperature for the period from 1994 to 2019 is −14.6°C (CEN, 2020). Maximum temperatures barely exceed 20°C, while minimum temperatures are about −50°C (CEN, 2020). The annual mean precipitation is 189 mm (ca. 50% of which is rain) (CEN, 2020). Permafrost at nearby Somerset Island and Devon Island has a thickness of >400 m (Smith & Burgess, 2002). At Bylot Island active-layer thickness varies from 1 m in sands and gravels to 0.3–0.7 m in peaty and silty soils (Allard et al., 2020). The vegetation at Bylot Island comprises graminoid and grass meadows, as well as shrub-forb tundra (Gauthier et al., 2011, Table 1).

2.2. Data Set

Data of 18 active layer soil pits and corresponding permafrost cores from Qarlikturvik Valley were included in the data set. Most of the sampling and coring (13 soil pits and corresponding permafrost cores) was performed in July 2017, July 2018, and July 2019. Data for another five locations were sourced from the ADAPT (2014, 2016) data set, which were collected in July 2013. Humid and mesic polygonal terrain was sampled in the central portion of the polygons to avoid cryoturbation near and over the ice wedges (Fortier & Allard, 2004). Thaw depths at the time of sampling ranged from 13 to 59 cm (for details see Table 1). A soil pit was dug and the thawed surface soil was sampled at fixed depths. Subsequently, permafrost cores were collected from the same location as the soil pits starting at the permafrost table using an earth auger equipped with a 10.8 cm diameter diamond carbide core barrel. The samples were stored frozen (−20°C) until analysis in the laboratory. Most permafrost cores were subsampled by horizon, but a small number (i.e., the ADAPT cores) were also subsampled at fixed depths. To study the vertical distribution of soil C and N within the top 100 cm of soil and to allow the comparison among geomorphological terrain units, total C and N, which were standardized by soil bulk density values, and C:N ratios, which are an index of the SOM degradability (Hobbie et al., 2002), were averaged for the following depth intervals: 0–5 cm, 5–20 cm, 20–60 cm, 60–100 cm. Initially, 20 cm intervals were chosen (e.g., Jobbágy & Jackson, 2000; Petrenko et al., 2016), but since there were no significant differences in C and N between 20–40 and 40–60 cm depths (Kruskal-Wallis Test: $X^2 = 0.281$, $p = 0.596$), data from these depth intervals were combined. The same was true for 60–80 and 80–100 cm depth intervals (Kruskal-Wallis Test: $X^2 = 0.892$, $p = 0.345$). The top 5 cm were analyzed separately to reflect the potentially high variability in topsoil C and N (Zubrzycki et al., 2013). Soil C and N contents (%) were determined using an elemental analyzer (LECO Corporation, St. Joseph, MI, US). Inorganic C was determined for all samples collected in 2018 and 2019 with a pH > 6.9, as alkaline soils are associated with carbonates (Jorgenson et al., 2013). These samples were analyzed for C after the organic C was oxidized in a muffle furnace (450°C, 8h, D. Wang & Anderson, 1998).

The data were grouped into three different geomorphological terrain units with a specific geomorphology and sediment type (e.g., Stephani et al., 2014): (a) alluvial fans (sampling locations/samples: 11/157), which are fed by taluses (i.e., the accumulations of rocks at the base of a cliff) on poorly consolidated Cretaceous-Tertiary sandstones and shales; (b) syngenetic low-center ice-wedge polygons (humid polygons sampling locations/samples: 3/32) formed in interstratified peat and eolian silt and sand of humid lowlands; and (c) epigenetic flat-center ice-wedge polygons (mesic polygons sampling locations/samples: 4/61) formed in glacigenic sediments of mesic hilly terrain (Table 1). Although alluvial fan sediments can be affected by frost-cracking and may contain syngenetic ice wedges at depth, the polygonal pattern at the alluvial fan studied was poorly expressed, both in terms of geometry (incomplete polygon), as well as height and width of the ridges (Table 1). Thus, the dominant landform and processes were considered alluvial.

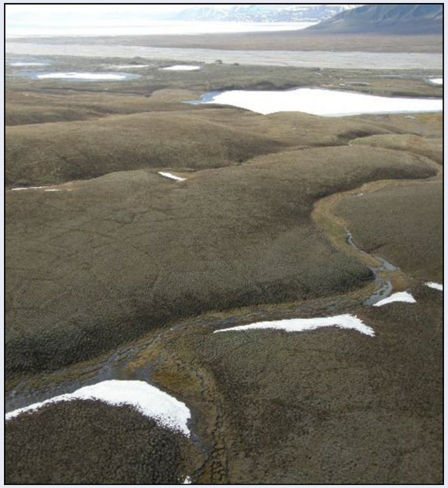
Finally, soil C stock values (kg m^{-2}) for each depth interval were calculated by multiplying the C concentration (kg kg^{-1}) by the dry soil bulk density (kg m^{-3}) and by the thickness of the depth interval (m). Subsequently, the soil C stock estimates of the depth intervals were summed to obtain a soil C stock estimate for each soil profile, which were then averaged to obtain C stock estimates for the top 100 cm of each geomorphological terrain unit (Mishra & Riley, 2012). The dry soil bulk density (kg m^{-3}) was calculated by dividing the dry weight with the volume of the sample (Obu et al., 2017).

2.3. Statistical Analysis

As the assumption of normality was not met by most of the variables, the Kruskal-Wallis test was used to determine the importance of geomorphological terrain unit (i.e., alluvial fan, humid low-center polygon, mesic flat-center polygon) on soil C stocks, N stocks, total C density, total N density, and C:N ratio of each soil depth interval (0–5 cm, 5–20 cm, 20–60 cm, 60–100 cm). Dunn's Test with Benjamini-Hochberg adjustment was used for multiple comparison of groups (Benjamini & Hochberg, 1995). For data that were normally distributed, a

Table 1

Area, Description and Specific Vegetation Communities (Cadieux et al., 2008) Associated With the Geomorphological Terrain Units (Alluvial Fan, Humid Polygonal Terrain, Mesic Polygonal Terrain)

Geomorphological terrain unit	 **Alluvial fan**	 **Humid polygonal terrain**	 **Mesic polygonal terrain**
Area (km^2)	17.595	20.171	4.8
Description	Presence of active, inactive and abandoned channels, syngenetic permafrost, thaw depths: 37.2 ± 4.6 cm (range 13–59 cm)	Low -centered polygons, some of which are high centered due to permafrost degradation, syngenetic permafrost, thaw depths: 27.3 ± 3.7 cm (range 20–32 cm)	Flat-centered polygons, epigenetic permafrost with cryoturbation, thaw depths: 18.3 ± 1.2 cm (range 15–20 cm)
Sediment	Sand/gravel	Peat/silt/sand	Sand/gravel/coble
General Vegetation Type	Shrub-forb tundra	Graminoid wet meadow	Grass mesic meadow
Plant Community	Salix ssp.—Astragalus alpinus/Forbs Sparse	Dupontia ssp.—Salix arctica/Moss Herbaceous Vegetation	Luzula nivali—Saxifraga oppositifolia/Herbaceous vegetation

one-way ANOVA was used to analyze the effect of geomorphological terrain unit on N density at 5–20 cm, and C:N ratio at 20–60 cm. For the former, the Tukey's HSD Test was used for multiple comparison of groups. All data were analyzed using R (R Core Team: www.R-project.org/).

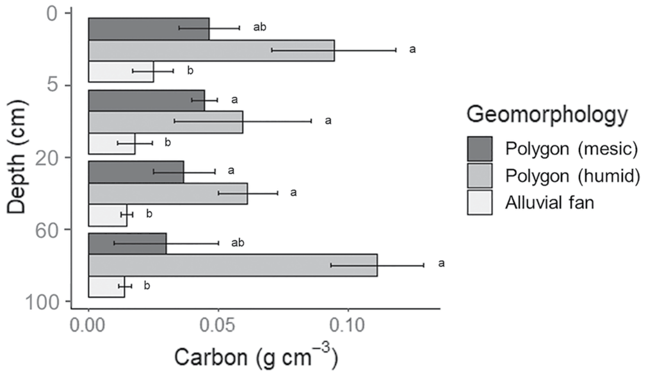


Figure 2. Distribution of total carbon ± standard error (g cm^{-3}) at different depths (0–5, 5–20, 20–60, and 60–100 cm) within a permafrost soil profile for various geomorphological terrain units (alluvial fan, humid polygonal terrain, mesic polygonal terrain). Letters indicate significant differences. Note the Y-axis is not linear.

3. Results

Soil C significantly differed among geomorphological terrain units (Figure 2, Table 2). At a depth of 0–5 cm pairwise comparison suggested alluvial fan C contents (0.025 ± 0.002 g cm^{-3}) were significantly lower than humid polygon C contents (0.094 ± 0.014 g cm^{-3}, p = 0.006). At 5–20 cm soil C contents were significantly lower in the alluvial fan (0.018 ± 0.002 g cm^{-3}) compared to those in polygonal terrain (humid: 0.059 ± 0.015 g cm^{-3}, p = 0.013; mesic: 0.045 ± 0.002 g cm^{-3}, p = 0.025). Similarly, at 20–60 cm C contents were significantly lower in the alluvial fan (0.015 ± 0.001 g cm^{-3}) compared to those in polygonal terrain (humid: 0.061 ± 0.007 g cm^{-3}, p = 0.007; mesic: 0.037 ± 0.007 g cm^{-3}, p = 0.05). Below 60 cm alluvial fan C contents were significantly lower than humid polygon C (p = 0.009). Inorganic C contents were very low ranging from 0.0% to 0.25% with a mean of 0.04 ± 0.0%.

Carbon concentration decreased with increasing soil depth in all geomorphological terrain units studied except humid polygonal terrain. In the alluvial fan C content decreased by 44% (from 0.025 ± 0.002 g cm^{-3} to 0.014 ± 0.001 g cm^{-3}) between the topsoil (0–5 cm) and the layer at depth (60–100 cm) (Figure 2). Similarly, in mesic polygonal terrain C content decreased by 36.2% (from 0.047 ± 0.006 g cm^{-3} to 0.03 ± 0.01 g cm^{-3}), while in humid polygonal terrain C content increased by 15.4% (from 0.094 ± 0.014 g cm^{-3} to 0.111 ± 0.01 g cm^{-3}) with increasing depth (Figure 2).

In addition, N content significantly differed among geomorphological terrain units (Table 2). At a depth of 0–5 cm pairwise comparison revealed alluvial fan N contents were significantly lower than mesic polygon N contents (p = 0.041). At 5–20 cm N contents were significantly lower in the alluvial fan (0.0012 ± 0.0001 g cm^{-3}) compared to those in polygonal terrain (humid: 0.0037 ± 0.0008 g cm^{-3}, p = 0.001; mesic: 0.0032 ± 0.0004 g cm^{-3}, p = 0.003). Below 20 cm alluvial fan N contents were significantly lower than humid polygon N contents (p = 0.007).

Table 2
The Effect of Geomorphological Terrain Units on Soil Carbon (C), Soil Nitrogen (N) and C:N Ratio for Various Soil Depth Intervals (0–5, 5–20, 20–60, and 60–100 cm), as Well as the Total for the Top 100 cm of Soil

Variable	Depth (cm)	Df	X^2/F-value	p
Total C	0–5	2	11.471[a]	**0.003**[*]
	5–20	2	11.056[a]	**0.004**[*]
	20–60	2	11.529[a]	**0.003**[*]
	60–100	2	9.45[a]	**0.009**[*]
	Total 100	2	12.895[a]	**0.002**[*]
Total N	0–5	2	8.221[a]	**0.016**[*]
	5–20	2	15.84[b]	**<0.001**[*]
	20–60	2	10.998[a]	**0.004**[*]
	60–100	2	10.562[a]	**0.005**[*]
	Total 100	2	12.895[a]	**0.002**[*]
C:N Ratio	0–5	2	0.382[a]	0.148
	5–20	2	0.321[a]	0.852
	20–60	2	0.576[b]	0.576
	60–100	2	8.301[a]	**0.016**[*]

[a]Kruskal-Wallis Test (X^2). [b]ANOVA (F-value). [*]Significant effects ($p < 0.05$) are highlighted.

Generally N concentrations decreased with increasing soil depth except in humid polygonal terrain, where N content was relatively stable within the top meter of soil (Figure 3). In the alluvial fan N content decreased by 40% (from 0.0015 ± 0.0002 g cm^{-3} to 0.0009 ± 0.0 g cm^{-3}) and in mesic polygonal terrain by 48.5% (from 0.0033 ± 0.0006 g cm^{-3} to 0.0017 ± 0.0004 g cm^{-3}) between the topsoil (0–5 cm) and the layer at depth (60–100 cm) (Figure 3).

The C:N ratios did not differ among geomorphological terrain units up to a depth of 60 cm (Table 2). C:N ratios ranged from 14.4 ± 1.3 (mesic polygon) to 18.3 ± 1.9 (alluvial fan) at a depth of 0–5 cm, from 14.8 ± 1.2 (mesic polygon) to 18.4 ± 3.3 (alluvial fan) at a depth of 5–20 cm, and from 15.7 ± 0.5 (humid polygon) to 18.0 ± 1.2 (mesic polygon) at a depth of 20–60 cm (Figure 4). However, at a depth of 60–100 cm C:N ratios differed among geomorphological terrain units (Table 2), due to the significantly higher C:N ratio of 26.3 ± 2.1 in humid polygonal terrain compared to 15.3 ± 0.9 in the alluvial fan (p = 0.013) (Figure 4). Furthermore, C:N ratios increased with increasing depth in polygonal terrain (humid: from 16.9 ± 1.0 to 26.3 ± 2.1; mesic: from 14.4 ± 1.3 to 17.0 ± 0.9), while C:N ratios decreased with increasing depth in the alluvial fan (from 18.3 ± 1.9 to 15.8 ± 0.3) (Figure 4).

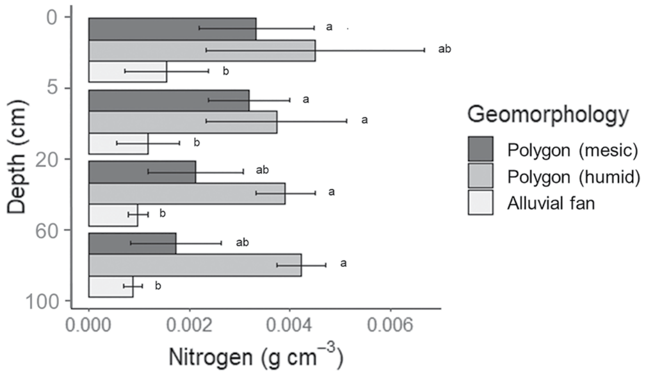


Figure 3. Distribution of total nitrogen ± standard error (g cm^{-3}) at different depths (0–5, 5–20, 20–60, and 60–100 cm) within a permafrost soil profile for various geomorphological terrain units (alluvial fan, humid polygonal terrain, mesic polygonal terrain). Letters indicate significant differences. Note the Y-axis is not linear.

Total soil C stocks for the top 100 cm differed significantly among geomorphological terrain units (Table 2). Soil C stocks were greatest in humid polygonal terrain (82.0 ± 4.1 kg m^{-2}), followed by mesic polygonal terrain (39.8 ± 9.0 kg m^{-2}), and alluvial fan (15.7 ± 0.6 kg m^{-2}, Figure 5a). Subsequent pairwise comparison showed that total C stocks differed significantly between alluvial fan and humid polygonal terrain ($p = 0.005$). Further, there was a significant difference in C stocks between alluvial fan and mesic polygonal terrain ($p = 0.024$).

Total soil N stocks for the top 100 cm also differed significantly among geomorphological terrain units (Table 2). Soil N stocks were greatest in humid polygonal terrain (4.0 ± 0.1 kg m^{-2}), followed by mesic polygonal terrain (2.3 ± 0.4 kg m^{-2}), and alluvial fan (1.0 ± 0.1 kg m^{-2}, Figure 5b). A pairwise comparison demonstrated that total N stocks differed significantly between alluvial fan and humid polygonal terrain ($p = 0.005$), as well as between alluvial fan and mesic polygonal terrain ($p = 0.024$).

In total, alluvial fans at Qarlikturvik Valley store about 0.277 Tg C and 0.018 Tg N in the top meter of soil. Humid polygonal terrain stores 1.654 Tg C and 0.081 Tg N, while mesic polygonal terrain stores 0.219 Tg C and 0.013 Tg N in the top meter of soil. Assuming inorganic C contents of 0.4%, alluvial fans store 0.226 Tg of SOC, while humid and mesic polygonal terrain store 1.643 and 0.218 Tg SOC, respectively.

4. Discussion

Geomorphological processes significantly affect soil C stocks. Lower soil C stocks in the alluvial fan setting compared to the polygonal terrain are in part the result of geomorphological processes characterized by strong erosive forces of the fluvial flows in the alluvial fan (Blair & McPherson, 1994), preventing the deposition of light particles such as OM (Powell, 1998). In periglacial environments, snowmelt, permafrost thaw, and rainfall in the catchment in spring and summer can create considerable discharge (de Haas et al., 2015). Discharge and fan gradient determine the depositional energy, influencing the characteristics of the sediment in an alluvial fan (Schillereff et al., 2014). In addition, sediment characteristics and supply, as well as proximity to fluvial sources may be important (Schillereff et al., 2014). For example, low levels of C in the alluvial fan may be the result of low levels of C of the source material and high influx of mineral sediments, acting as dilution factor (Berhe et al., 2007; Doetterl et al., 2012). Furthermore, fluvial flows may transport a significant fraction of the eroded material into the periglacial river, which constrains the extent of the alluvial fans, preventing the deposition and accumulation of soil and OM (Clarke et al., 2010) and associated soil C stocks at the fan base.

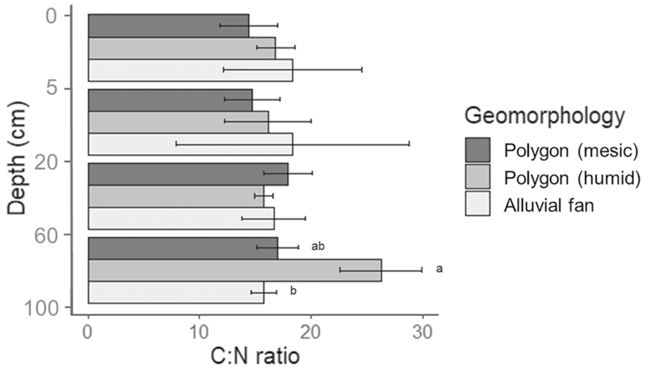


Figure 4. C:N ratios at different depths (0–5, 5–20, 20–60, and 60–100 cm) within a permafrost soil profile for various geomorphological terrain units (alluvial fan, humid polygonal terrain, mesic polygonal terrain). Letters indicate significant differences. Note the Y-axis is not linear.

Plant productivity is another important factor influencing soil C stocks by adding OM to the soil, as soil C stocks reflect the balance between C inputs via primary production or deposition, and outputs via erosion, decomposition, volatilization and leaching of organic compounds (Amundson, 2001). Indeed, vascular vegetation cover has been shown to have the strongest correlation with SOC stocks in the Thule region (Howarth Burnham & Sletten, 2010). Since geomorphic processes (e.g., erosion and sediment deposition) interfere with plant growth in alluvial fans (Ishida et al., 2010; Lane et al., 2016; Tomczyk et al., 2019), greater plant productivity in the polygonal terrain may also have contributed to higher SOC stocks observed here. However, soil development in late stages of fan development or in fan sections with abandoned channels facilitates changes in plant diversity (Ishida et al., 2010; Lane et al., 2016; Tomczyk et al., 2019), thus plant productivity (Fraser et al., 2015; Grace et al., 2016; Grime, 1973). Additionally, changes in vegetation cover potentially reduce the erodibility of the soil, as vegetation alters soil properties such as aggregate stability (Gyssels et al., 2005; Ola et al., 2015). At our study site the shrub *Salix richardsonii* increasingly

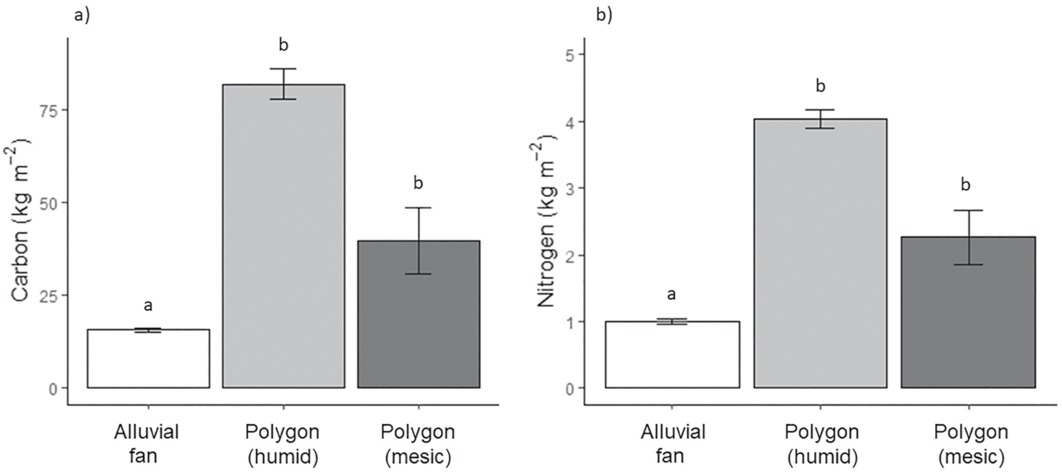


Figure 5. (a) Total soil carbon stocks ± standard error (SE) (kg m^{-2}) and (b) total nitrogen stocks ± SE (kg m^{-2}) for the top 100 cm of permafrost soil in various geomorphological terrain units (alluvial fan, humid polygonal terrain, mesic polygonal terrain). Letters indicate significant differences.

colonizes alluvial fans (Tremblay, 2018, Table 1), which may increase the soil C stocks in the alluvial fans at Qarlikturvik Valley in the long-term. However, differences in soil C stocks between polygonal terrain units may partly be explained by differences in soil moisture (Cadieux et al., 2008; Gauthier et al., 2011), as anoxic conditions slow down decomposition (Lee et al., 2012; Zona et al., 2012). Similarly, the presence of syngenetic permafrost may also be responsible for better preserved soil C stocks in humid polygons, as opposed to epigenetic permafrost in mesic polygons (Ewing et al., 2015).

Comparable C stock estimates from the Arctic are rare. However, by upscaling data from eight soil pedons, SOC stocks for the top meter of soil of 17.8 ± 11.0 kg m^{-2} have been calculated for the region (Hugelius et al., 2014). This C stock estimate is much lower than the estimates for polygonal terrain at Qarlikturvik Valley (82.0–39.8 kg m^{-2} for humid and mesic polygonal terrain respectively), but similar to estimates of 15.7 ± 0.6 kg m^{-2} for the studied alluvial fan area. This highlights the importance of considering geomorphological terrain units for soil C stock assessments. Soil C stocks at Spitsbergen, Norway for humid tundra (26.3 kg m^{-2}, Weiss et al., 2017) are much lower than the C stocks measured in both types of polygonal terrain on Bylot Island (Table 3). However, the C stock estimates presented here for humid polygonal terrain are strikingly similar to SOC stock estimates from Herschel Island, Canada (84.1 kg m^{-2}, Obu et al., 2017, Table 3). Conversely, alluvial fan C stocks presented here (15.7 kg m^{-2}) are much lower than SOC stocks for alluvial fans on Herschel Island (42.5 kg m^{-2}, Obu et al., 2017, Table 3) or at Zackenberg, Denmark (42.7 kg m^{-2}, Palmtag et al., 2018, Table 3). Thus, soil C stocks are highly variable among sites even within the same geomorphological terrain unit and more studies are needed to improve circumpolar soil C estimates, which are more precise when geomorphology is considered.

Table 3
Soil Organic Carbon (SOC) Stocks (kg m^{-2}) for Alluvial Fans and Polygonal Terrain From Arctic Regions

Terrain unit	Location		SOC stock (kg m^{-2})	Study
Alluvial Fan	Herschel Island, Yukon	69.58°N, 139.08°W	42.5	Obu et al. (2017)
	Zackenberg, Greenland	74.47°N, 20.57°E	42.7	Palmtag et al. (2018)
	Bylot Island, Nunavut	73.10°N, 80.00°W	15.6[a]	This study
Polygonal Terrain	Herschel Island, Yukon	69.58°N, 139.08°W	84.1	Obu et al. (2017)
	Spitsbergen, Svalbard	77.88°N, 20.98°E	26.3	Weiss et al. (2017)
	Bylot Island, Nunavut	73.10°N, 80.00°W	39.6 to 81.7[a]	This study

[a] After subtracting 0.4% of total C for inorganic C.

Geomorphological terrain type also influences soil N levels. Soil N is related to soil OM inputs (Jobbágy & Jackson, 2000). Thus, like soil C, the distribution of soil N across geomorphological terrain units reflects the absence of erosive forces at the study sites located in polygonal terrain, as well as differential inputs from the vegetation (Hobbie, 1996), where N has essentially been accumulating throughout the late Holocene. Other factors that may influence the distribution of N are temperature and hydrology, affecting decomposition (Schuur et al., 2008), sediment characteristics, and geochemistry, influencing OM stabilization (Evgrafova et al., 2018), as well as the presence and abundance of birds such as geese (Gauthier et al., 1996). Total N stocks in the humid polygonal terrain at Qarlikturvik Valley (4.0 ± 0.1 kg m^{-2}) are four times greater than those at the Lena River delta (1.1 kg m^{-2}, Zubrzycki et al., 2013), but similar to those reported at Herschel Island (4.6 kg m^{-2}, Obu et al., 2017). Conversely, N stocks in the alluvial fan here (1.0 ± 0.0 kg m^2) are three times lower than N stocks at Herschel Island (3.4 kg m^{-2}, Obu et al., 2017), but similar to those at Zackenberg valley (1.1 kg m^{-2}, Palmtag et al., 2018). These C and N dynamics are also reflected in the relatively high C:N ratios indicating limited degradation of OM or N availability in these soils, both of which are very common phenomena in Arctic ecosystems (Chapin & Shaver, 1996; Chapin et al., 1975; Hobbie et al., 2002; Mack et al., 2004).

Carbon and N concentrations decreased with increasing soil depth in all terrain units studied except humid polygonal terrain. Decreases in SOC with depth have frequently been reported in circumpolar regions (e.g., Obu et al., 2017; Weiss et al., 2017). Indeed, Hugelius et al. (2014) found that 30%–50% of the total SOC stored up to a depth of 300 cm are stored within the top-soil (0–30 cm). As for N, a 44% decrease with increasing depth up to 100 cm has been reported in Zackenberg valley (Palmtag et al., 2018). Greater C and N contents at the soil surface are the result of fresh OM inputs from vegetation (Jobbágy & Jackson, 2001; Lorenz & Lal, 2005). As fresh litter and, depending on setting, eolian or alluvial sediment is added to the soil surface, it buries previously deposited litter in various stages of decay, resulting in the widely observed decreases in soil C and N with depth (Jobbágy & Jackson, 2001; Lorenz & Lal, 2005). Relatively low levels of C and N at depth may reflect initial soil formation processes after glacier retreat (Wietrzyk-Pełka et al., 2020). The increase in C levels in humid polygonal terrain at 60–100 cm may have accumulated under a different vegetation and climate in the past facilitating OM production, as well as high (eolian) sedimentation facilitating the upward movement of the permafrost table thereby preventing decomposition (Allard, 1996; Fortier et al., 2006). These unexpected high levels of C and N at depth highlight the need to sample depths below 100 cm to accurately estimate soil C and N stocks expressed earlier (e.g., Harden et al., 2012). This may be particularly true for alluvial fans, which are characterized by the frequent deposition of potentially large volumes of mineral sediment, diluting soil C concentrations. However, due to the potentially large spatial variability in soil characteristics (Siewert et al., 2021) further sampling in alluvial fans of various developmental stages, humid and mesic polygonal terrain at the local and regional scale is needed.

5. Conclusions

Soil C and N contents in the top 1 m at Qarlikturvik Valley differ among dominant vegetated geomorphological terrain units and are greater in polygonal terrain than in the alluvial fan area. This is likely due to geomorphological processes in the alluvial fan (i.e., fluvial flows and associated sediment transport), differences in vegetation cover and soil characteristics such as moisture levels and oxygen availability, as well as permafrost processes. Carbon stocks in polygonal terrain at Qarlikturvik Valley are 2.2 to 4.6 times greater (39.8–82.0 kg C m^{-2}) than estimates proposed in an initial assessment of Arctic soil C stocks (Hugelius et al., 2014). Alluvial fans store 15.7 kg C m^{-2}, which is in line with earlier assessments (Hugelius et al., 2014). This highlights the need for an increased resolution considering the numerous geomorphological terrain units frequently found in Arctic regions to estimate representative soil C and N stocks and to predict greenhouse gas (e.g., CO_2, CH_4, and N_2O) emissions from Arctic regions.

Data Availability Statement

The data used to determine the effect of geomorphological terrain unit on soil carbon and nitrogen stocks at Bylot Island is available at ZENODO via (Ola et al., 2022) https://doi.org/10.5281/zenodo.6753897.

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