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Regional and local scale variations in soil organic carbon stocks in West Greenland

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Abstract

The soil organic carbon (SOC) pool of the Northern Hemisphere contains about half of the global SOC stored in soils. As the Arctic is exceptionally sensitive to global warming, temperature rise and prolonged summer lead to deeper thawing of permafrost-affected soils and might contribute to increasing greenhouse gas emissions progressively. To assess the overall feedback of soil organic carbon stocks (SOCS) to global warming in permafrost-affected regions the spatial variation in SOCS at different environmental scales is of great interest. However, sparse and unequally distributed soil data sets at various scales in such regions result in highly uncertain estimations of SOCS of the Northern Hemisphere and here particularly in Greenland. The objectives of this study are to compare and evaluate three controlling factors for SOCS distribution (vegetation, landscape, aspect) at two different scales (local, regional). The regional scale reflects the different environmental conditions between the two study areas at the coast and the ice margin. On the local scale, characteristics of each controlling factor in form of defined units (vegetation units, landscape units, aspect units) are used to describe the variation in the SOCS over short distances within each study area, where the variation in SOCS is high. On a regional scale, we investigate the variation in SOCS by comparing the same units between the study areas. The results show for both study areas that SOCS are with 8 kg m^{-2} in the uppermost 25 cm and 16 kg m^{-2} in the first 100 cm of the soil, *i.e.*, 3 to 6 kg m^{-2} (37.5%) higher than existing large scale estimations of SOCS in West Greenland. Our approach allows to rank the scale-dependent importance of the controlling factors within and between the study areas. However, vegetation and aspect better explain variations in SOCS than landscape units. Therefore, we recommend vegetation and aspect for determining the variation in SOCS in West Greenland on both scales.

Key words: Arctic / landscape classification / permafrost-affected soils / tundra vegetation

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Supporting Information available online

1 Introduction

Soils store up to 3000 Pg carbon worldwide, which is twice the amount of the biosphere and the atmosphere together (*Köchy* et al., 2015). The northern circumpolar permafrost region stores about 1300 Pg soil organic carbon (SOC), whereof 217 Pg SOC are stored in the top 30 cm and 472 Pg in the first meter of the soil (*Hugelius* et al., 2013, 2014). The increase in air temperature of the Arctic overrides the global mean significantly over the last decades (*IPCC*, 2019), assuming a much stronger influence on permafrost soils than previously expected (*Chadburn* et al., 2017). This causes environmental alterations accelerating microbial breakdown of organic carbon and enhancing the release of the greenhouse gases to the atmosphere (*Schuur* et al., 2015). To assess the impact of global warming and greenhouse gas emission in permafrost-affected regions the spatial distribution and the amount of SOC stored in the soils have to be estimated as precise as possible.

However, the estimation of soil organic carbon stocks (SOCS) of permafrost-affected soils is highly uncertain as, for one reason, there is an unbalanced distribution of studies across the Arctic focusing on Alaska, Siberia and Canada, while Greenland is underrepresented (*Tarnocai* et al., 2009; *Hugelius* et al., 2014; *Köchy* et al., 2015; *Ping* et al., 2015). For West Greenland predominantly Umbrisols and Cambisols are reported (*cf Jensen* et al., 2006; *Bradley-Cook* and *Virginia*, 2016; *Petrenko* et al., 2016; *Kühn* and *Henkner*, 2019), which could store a significantly higher amount of SOC than thin and less developed soils in East and North Greenland (*Elberling* et al., 2008a, 2008b; *Palmtag* et al., 2015, 2018).

On a regional scale, SOCS are typically related to climate in terms of precipitation and temperature (*Post* et al., 1982). In West Greenland, mean annual air temperature (MAT) and mean annual precipitation (MAP) decrease from the coast at Sisimiut (MAT; MAP: –3.5°C; 383 mm) to the ice margin at Kangerlussuaq (–5.7°C; 149 mm) over a distance of 150 km on the regional scale (*Cappelen* et al., 2001; *Carstensen* and

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Jørgensen, 2009). At the ice margin, the air temperature is 3 K higher during the growing season (May–September) and 5 K lower from October until April than at the coast (*Cappelen* et al., 2001). Vegetal activity (*CAVM Team*, 2003) and permafrost thickness (*Van Tatenhove* and *Olesen*, 1994) increase towards the ice margin. Another interpretation of lower amounts of SOCS with increasing distance from the coast to the ice margin in West Greenland is related to the Holocene deglaciation history of the Greenland Ice Sheet, with decreasing age of exposed surfaces from the coast to the ice margin (*Levy* et al., 2012; *Bradley-Cook* and *Virginia*, 2016). However, these findings are in contrast with large scale estimates of SOCS in West Greenland showing no differences between the coast and the ice margin (*Jones* et al., 2009; *Hugelius* et al., 2014; *Köchy* et al., 2015).

On a local scale, vegetation and topography influence SOCS distribution in Greenland (*Ozols* and *Broll*, 2003; *Jensen* et al., 2006; *Elberling* et al., 2008b; *Horwath Burnham* and *Sletten*, 2010; *Henkner* et al., 2016) and also in other Arctic environments (*Palmtag* et al., 2015, 2018; *Siewert* et al., 2015, 2016; *Wojcik* et al., 2019). The topography affects both the local and the regional climate, thaw depth of the active layer, deflation, erosion by water and related accumulation processes (*Van Tatenhove* and *Olesen*, 1994; *Müller* et al., 2016). Katabatic winds take control in east–west direction, with more arid and colder conditions close to the ice margin over distances of some hundred meters to a few kilometers (*Müller* et al., 2016). In addition, topsoil SOCS are connected to distribution pattern of vegetation and soil moisture (*Henkner* et al., 2016), whereas slope processes, cryoturbation and active layer thickness affect the vertical distribution of SOC in the subsoil (*Bockheim*, 2007; *Palmtag* et al., 2015, 2018; *Siewert* et al., 2015, 2016; *Wojcik* et al., 2019). However, vegetation pattern and the soil water regime are related to topographic positions as well (*Elberling* et al., 2008a), mainly determined by the local Holocene deglaciation history resulting in moraines stretching across valleys from north to south (*Henkner* et al., 2016). Given such strong differences in controlling environmental conditions on various scales, a similar fluctuation of SOCS is expected. If that holds true, such scale-dependent variations in SOCS cannot be described by the existing large scale estimations satisfactory.

The objectives of this study are to compare and evaluate three controlling factors for SOCS distribution (vegetation, landscape, aspect) at two different scales (local, regional). The regional scale reflects the different climate conditions and related vegetation patterns on SOCS between two study areas. On the local, characteristics of each controlling factor in form of defined units (vegetation units, landscape units, aspect units) are used to describe the variation in SOCS over short distances within each study area. On a regional scale we investigate the variation in SOCS by comparing the same units between the study areas. This approach allows ranking the scale-dependent importance of the controlling factors of SOCS within and between the study areas.

2 Material and methods

2.1 Study areas

The study area at the coast (SISI) is 1.5 km^2 in size and located around 4 km east to the city of Sisimiut (66°57′ N, 53°33′ W). The coastal area is characterized by oceanic climate conditions with frequently occurring fog, coastal westerly winds, MAT of –3.5°C and MAP of 383 mm (*Cappelen* et al., 2001; *Carstensen* and *Jørgensen*, 2009). SISI is located within a deep valley with northeast–southwest orientation and steep north- and south-facing slopes. The northern boundary of the study area consists of steep slopes (> 30°) with sparse vegetation cover and thin soils. A lake defines the western boundary and a small river the eastern boundary. The small river crosses the study area from the northeast to the southwest characterized by adjacent flat areas and depressions in smooth transition with slightly inclined slopes and moraines. A ridge with steep north-facing slopes marks the southern boundary of the study area (Fig. 1).

The study area at the ice margin (RUSS) comprises around 1.8 km^2 and is located directly at the ice margin, around two kilometres west of the Russell Glacier (67°6′ N, 50°17′ W), which is an outlet glacier of the Greenland Ice Sheet. The ice margin area is characterized by an Arctic continental climate with MAT of –5.7°C and MAP of 149 mm and katabatic winds blowing down from the Greenland Ice Sheet predominantly to the west (*Cappelen* et al., 2001; *Carstensen* and *Jørgensen*, 2009). RUSS is located in an east–west oriented valley with steep north- and south-facing slopes and lakes in the east and west which define the boundaries of the study area. Sand dunes occur in the northeastern part caused by the katabatic winds taking up sediment from the outwash plains (*cf Müller* et al., 2016). Different terminal moraines cross the valley in north-south direction (Fig. 1).

Mountain vegetation on non-carbonate bedrock, *i.e.*, mostly granite in SISI and gneiss in RUSS, defines the vegetation in both study areas (*CAVM Team*, 2003; *Henriksen*, 2008). Sedges cover depressions, flat and bankside areas, whereas mosses, lichens and prostrate dwarf shrubs grow on steep slopes and ridges. Dwarf shrubs < 40 cm in height in SISI and > 40 cm in RUSS occur in wind sheltered areas and slightly inclined slopes. Since the last deglaciation, predominantly periglacial processes reshaped the glacial landscape (*Stäblein*, 1977; *Ozols* and *Broll*, 2003; *Willemse* et al., 2003; *Henriksen*, 2008; *Müller* et al., 2016). The maximal possible time for soil formation since the last deglaciation is around 10,000 years in SISI and 6,800 years in RUSS (*cf Bradley-Cook* and *Virginia*, 2016). Dominant soils are acid haplic Cambisols and Cryosols in both study areas (*Stäblein*, 1977; *Jones* et al., 2009; *Henkner* et al., 2016; *Kühn* and *Henkner*, 2019). The majority of soils at steep slopes, moraine crests, ridges and summits are less developed on coarse substrate with an active layer thickness > 200 cm. Wind sheltered locations of dunes and at slightly inclined slopes are characterized by warm and dry soil conditions and sandy substrate. On these locations, soil formation results in organic rich soils of which some are buried by aeolian sediments. Soils in depressions, flat and bankside area have thick organic horizons with

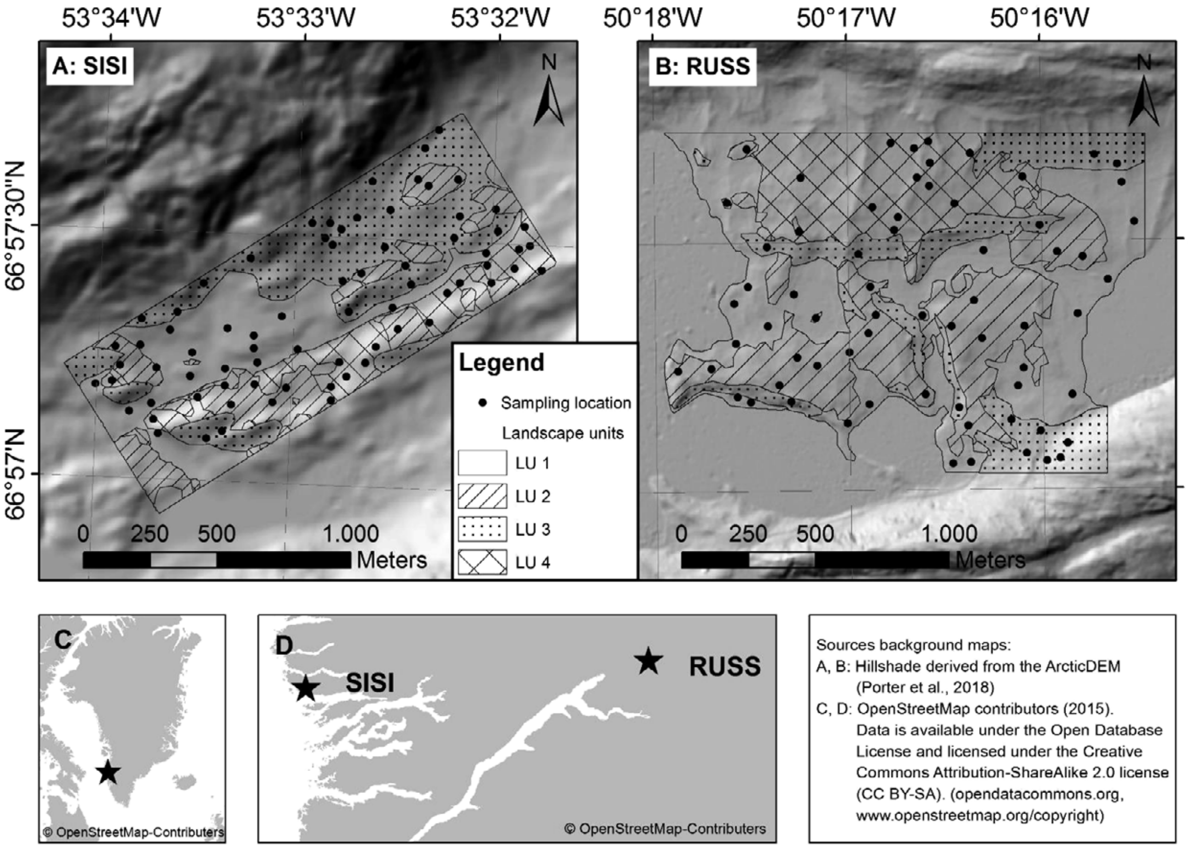

Figure 1: Study areas near Sisimiut (SISI) at the coast and close to the Russell Glacier (RUSS) at the ice margin of the Greenland Ice Sheet with sampling locations and landscape units.

silty texture, high soil moisture content and a thin active layer (60.08 ± 35.34 cm). Further impressions of the study areas are given by photographs in the online supplement (S1, S2).

2.2 Delineation of landscape units and sampling design

Landscape units (LU) are delineated as spatial entities that represent the spatial extend of homogenous landforms according to the deglaciation history and geomorphology of the land surface (Tab. 1). To structure the topography of the study areas, we used a set of local, regional and combined terrain covariates which are relevant for the spatial distribution of SOCS (Tab. S3, supplementary material). The terrain covariates are derived from a digital elevation model with a resolution of 5 × 5 m computed from aerial images from the Geodetic Institute of Denmark using VisualSFM (*Wu*, 2011; *Wu* et al., 2011), where structure from motion is combined with photogrammetry to estimate three dimensional terrain surface objects from satellite image sequences (*Carrivick* et al., 2016).

To delineate the LU, we used k-means cluster analysis for automated and unsupervised classification of terrain covariates (*Burrough* et al., 2000; *Schmidt* et al., 2010). The aim of the cluster analysis is to divide the study areas into homogeneous classes with high interclass variance and small intraclass variance (*Webster* and *Beckett*, 1968; *Everitt*, 1980). The selection of the number of clusters aims at a best-structured and less-fragmented representation of the two study areas. According to *Schmidt* et al. (2010) we set k = 10 as maximum number of LUs to address feasibility of the subsequent sampling design and determined the optimal number of classes by using the number of fragments and their perimeter per class (Fig. 2). The smaller the number of fragments and the perimeter, the lower the degree of fragmentation of the classes and thus optimally suited for the designation of LU. The intersection represents the optimal size of k which is both 3.68 and 4.34 for SISI and 4.18 for RUSS. Finally, we chose four classes for LUs for both study areas. The paired t-test of the terrain parameters of each LU ensures the pairwise comparability of related LUs between both study areas (Tab. 1).

Table 1: Results of t-test (significance level, α = 0.05) to verify the comparability of each LU between SISI and RUSS and the major landform elements they represent.

Landscape unit	Landform element	*p*-value (t-test)
LU1	Depression, flat and bankside area	0.037
LU2	Moraine crest, ridge, summit	0.027
LU3	Plateau area	0.019
LU4	Steep slope	0.020

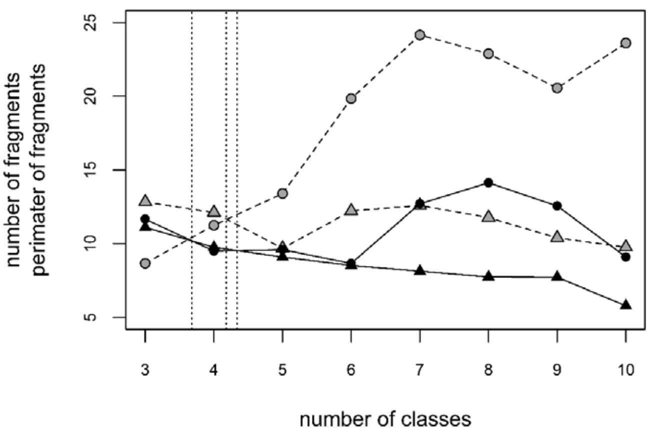

Figure 2: Determination the optimal number of classes (c) in SISI (black) and RUSS (grey) by using the number of fragments (points) and their perimeter (triangles) per class. The intersections represent the optimal number of classes which is both 3.68 and 4.34 for SISI and 4.18 for RUSS.

In total 140 sampling points were proportionally allocated to the LUs according to surface percentage and fragmentation. The sampling points were randomly distributed based on software (*Create Random Points* tool, ArcGIS Desktop 10.3; *ESRI*, 2014) within each LU (Fig. 1).

2.3 Field work, laboratory and statistical analysis

During a field campaign in summer 2016, vegetation cover (VEG) was recorded by species and their growth height according to *Bliss* (2000) (Tab. 2) and the aspect (ASP) was determined at all sampling locations. We used a hand-driven, half-open Pürckhauer auger (0–100 cm; slot width 18 mm) with an extension (100–200 cm; slot width 16 mm) for sampling of SOC and bulk density (BD) (*e.g.*, *Don* et al., 2007) at four depth increments (0–25, 25–50, 50–100, and 100–200 cm). Only unfrozen ground was sampled. The first depth increment (D1) was set to 0–25 cm as according to an earlier field survey the maximal thickness of the upper organic horizon was found to be 25 cm in both study areas. Since the minimal thickness of the active layer (AL) is around 50 cm at comparable landscape conditions in West Greenland, the second depth increment (D2) was set to 25–50 cm (*cf Bradley-Cook* et al., 2016; *Henkner* et al., 2016). The third depth increment (D3) was set to 50–100 cm, because a large amount of SOC can be stored in the subsoil (*Tarnocai* et al., 2009; *Hugelius* et al., 2014). We set the fourth depth increment (D4) to 100–200 cm to include soil heterogeneity caused by cryoturbation (*Ping* et al., 1998).

For SOC analysis, we sampled three soil cores at each sampling location to have three replicates of each depth increment over the complete depth. The replicates of each depth increment were bulked. If a depth increment could not be sampled completely due to frozen subsoil conditions or bedrock, the SOCS of the not-sampled part was set to 0. Due to the subsoil conditions 140 samples were taken from D1, 138 samples from D2, 127 samples from D3, and 91 samples from D4. We sampled 16 locations for BD, covering all LUs. BD samples were collected from the middle of each depth increment (10–15, 35–40, 72.5–77.5, and 147.5–152.5 cm) from the soil cores.

Samples for SOC were dried at 40°C, sieved (< 2mm) and analyzed using oxidative heat combustion at 1150°C in a helium atmosphere (element analyzer Vario EL II, Elementar Analysesysteme GmbH, Germany, in CN mode). Measurements below the detection limit (carbon: 0.2%) were set to zero. Since the gasvolumetrical determination of carbonate content according to Scheibler (*Rothenhöfer* et al., 2000) was negative for all samples, we assumed that total carbon content equals SOC (%). The BD samples were dried at 105°C to determine the mass [*mass*, (g)] gravimetrically to calculate the BD (g cm^{-3}) according to Eq. (1) and Eq. (2), and to determine the mass proportion of the coarse fraction (%) > 2 mm [CF (%)] to calculate the SOCS (kg m^{-2}) according to Eq. (3) (*Scholten* et al., 2017). Equation (2) is necessary to calculate the volume of a sample taken from a half-open Pürckhauer auger.

$$BD = mass \times Vs^{-1}, \quad (1)$$

$$Vs = Vc + 0.5 \times Ve = w \times h \times l + 0.5(\pi \times a \times b \times l), \quad (2)$$

where Vs [volume of the sample (cm^3)] is a combination of the volume of a cuboid Vc (cm^3) and the half of an ellipse Ve (cm^3); w is the slot width of the auger, h the height of the cuboid and l the depth of the BD samples; a is the half of the slot width w and b the height of the ellipse; w, h, l, a, and b are given in (cm).

Table 2: Vegetation units according to *Bliss* (2000).

Vegetation unit		Dominant species	Growth height (cm)	Percentage area (%) (SISI/RUSS)	Position
VEG1	Dwarf shrub heath tundra	*Betula nana, Dryas integrifolia*	5–20 cm	28 / 10	Steep slopes, ridges, moraine crests, summits
VEG2	Low shrub tundra	*Betula nana*	20–40 cm	38 / 39	Slopes
VEG3	Tall shrub tundra	*Salix glauca*	> 40 cm	4 / 18	Slightly inclined slopes
VEG4	Graminoid-moss tundra	*Carex rariflora Eriophorum angustifolium*	5–20 cm	30 / 33	Depressions, flat areas, bankside areas

$$SOCS = SOC \times BD \times D \times (1 - CF), \quad (3)$$

where D (cm) is the thickness of the depth increments D1–D4. If the entire depth increment could not be sampled due to bedrock or the permafrost table, the actual depth was used for D. For analysing field and lab data we used the statistical software R and the *stats* package version 3.4.2 (*R Development Core Team*, 2013). We used ANOVA to determine statistical connections.

3 Results

First, we present the results on the local variation in SOCS related to VEG, LU, and ASP within each study area. Regional differences between the study areas are explained in chapter 3.2.

3.1 Local scale variations in SOCS

3.1.1 Vegetation units

Dwarf shrub heath tundra (VEG1) is predominant at steep slopes, moraine crests, ridges and summits characterized by sandy texture at 0–25 cm with increasing silt content down to 100 cm depth, a thick active layer and a wide range of soil moisture content in both study areas. Low shrub tundra (VEG2) and tall shrub tundra (VEG3) mainly cover slightly inclined slopes and wind sheltered areas. Topsoil material (0–25 cm) has higher silt content on locations covered by VEG2 and VEG3 compared to VEG1. Graminoid-moss tundra (VEG4) has highest soil moisture content compared to the other VEG.

In SISI, topsoil SOCS are highest for VEG3 (12.20 ± 4.76 kg m^{-2}) which is 27% higher than for VEG2 and VEG4 and 7.52 kg m^{-2} higher than for VEG1. Within 25–50 cm and 50–100 cm, SOCS are highest for VEG4 but highest for VEG3 within 100–200 cm. In general, SOCS are lowest for VEG1 at all depth increments in SISI (Fig. 3). The uppermost 25 cm of soil show no significant correlation between VEG and SOCS in SISI (Tab. 3).

In RUSS, the general picture is the same as in SISI. SOCS are highest for VEG3 (10.88 ± 2.20 kg m^{-2}) which is 31% higher than for VEG2 and VEG4 and 54% higher than for VEG1 within 0–25 cm (4.98 ± 4.03 kg m^{-2}). Besides, SOCS are highest for VEG3 (25–50 cm, 50–100 cm) as well but 80% lower than for VEG2 and VEG4 within 100–200 cm (Fig. 3). For the uppermost 25 cm, VEG and SOCS are significantly correlated (Tab. 3).

3.1.2 Landscape units

The landscape units represent specific landform elements similar in both study areas (Tab. 1). Sampling locations in LU1, dominated by graminoid-moss tundra (VEG4), are characterized by sandy texture, wet and cold soil conditions and low active layer thickness in both study areas. In both study areas, in LU2 tall shrub tundra (VEG4) is not existent and LU3 is dominated by low shrub tundra (VEG2).

Table 3: Anova (F-Value) of environmental parameters and significance (*p*-values: *** < 0.0001, ** < 0.001, * < 0.05) in SISI and RUSS.

Study area		Depth (cm)	LU	VEG	ASP
SISI	SOCS	0–25	1.82	1.85	1.48
(coast)		25–50	1.39	2.40	0.70
		50–100	1.32	2.23	1.03
		100–200	0.04	3.00*	2.72*
	LU			0.02	3.66*
	VEG				1.65
	ASP				
RUSS	SOCS	0–25	4.09*	4.64*	2.14
(ice margin)		25–50	5.85*	0.91	0.66
		50–100	1.16	0.96	0.97
		100–200	0.72	1.86	0.46
	LU			0.33	0.71
	VEG				1.94
	ASP				

In SISI, SOCS are highest within 0–25 cm in LU3 (10.82 ± 8.83 kg m^{-2}), which is 37% higher than in LU1, 42% in LU2 and 44% in LU4. But SOCS are lowest in LU2 within all depth increments below 0–25 cm. Within 100–200 cm, there is no distinct difference in SOCS of the different LUs (Fig. 3).

In RUSS, SOCS are lowest in LU2 within all depth increments decreasing from 5.66 ± 3.00 kg m^{-2} (0–25 cm) to 3.01 ± 2.98 kg m^{-2} (100–200 cm). In LU1, SOCS are highest within all depth increments being 50–60% higher than within all depth increments in LU2 (Fig. 3). SOCS are with 8.28 ± 3.87 kg m^{-2} and 8.54 ± 3.54 kg m^{-2} similar in LU3 and LU4 within the uppermost 25 cm. There is a significant correlation between LU and SOCS within 0–25 and 20–50 cm in RUSS (Tab. 3).

3.1.3 Aspect

In SISI, SOCS are lowest (mean < 5 kg m^{-2}) on east-, north-west- and west-facing locations and with up to about 30 kg m^{-2} highest on south-facing (S, SE) locations in 0–25 cm (Fig. 4). Average SOCS on north-facing locations are 7.75 ± 5.22 kg m^{-2} in the uppermost 25 cm, which is about 2 kg m^{-2} respectively 1 kg m^{-2} higher than within 25–50 cm and 50–100 cm but about 2 kg m^{-2} lower within 100–200 cm. There is a significant relationship between SOCS and ASP in SISI at 100–200 cm (Tab. 3).

In RUSS, there is a large difference up to 15.17 kg m^{-2} between the lowest on east-facing locations (4.95 ± 1.19 kg m^{-2}) and highest SOCS on west-facing locations within the first depth increment. Generally, soils on north-facing locations show higher SOCS (NE, N, NW: 8.91 ± 3.25 kg m^{-2}) than on south-facing

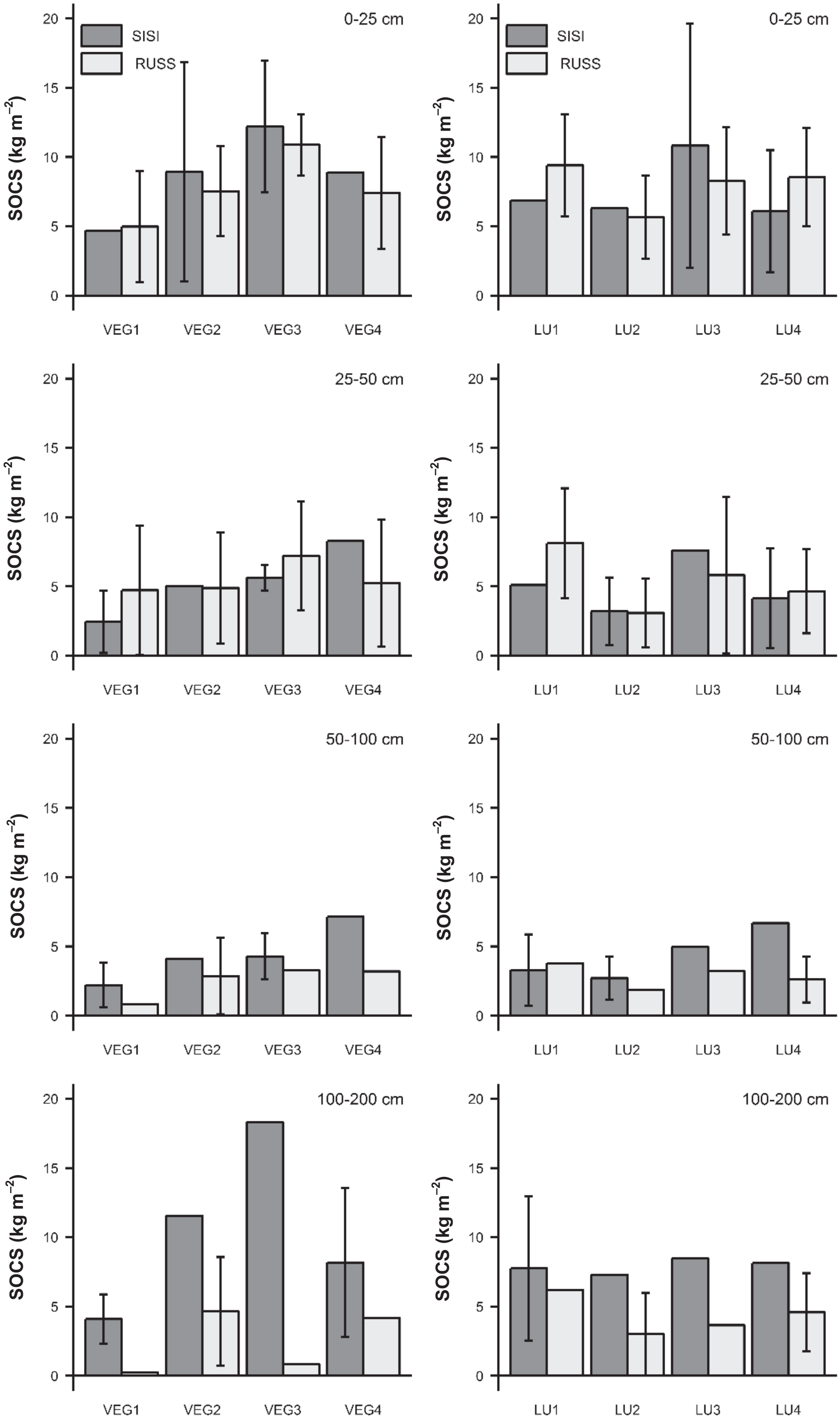

Figure 3: Variation in SOCS (mean, SD) by VEG and LU in SISI and RUSS. Missing SD in 100–200 cm relates to *n* = 1 and SD > mean.

locations (SE, S, SW: 7.16 ± 3.84 kg m^{-2}) (Fig. 4). Tall shrub tundra (VEG3) is only present on south- and southeast-facing locations.

3.2 Regional scale variations in SOCS

On average, SOCS are similar in both study areas within 0–25 cm (around 8 kg m^{-2}) and 25–50 cm (around 5 kg m^{-2}) but have distinct differences within 50–100 cm and 100–200 cm with 36% respectively 53% higher SOCS in SISI than in RUSS. In addition, maximum SOCS within all depth increments are 47–68% higher in SISI than in RUSS (Tab. 4).

3.2.1 Vegetation units

In SISI, SOCS (0–25 cm) are 11 to 17% higher for VEG2, VEG3 and VEG4, but 6% lower for VEG1 than in RUSS. Over all soil depth increments, SOCS are higher in SISI compared to RUSS. Only for VEG3, RUSS shows with 7.20 ± 3.93 kg m^{-2} higher SOCS within 25–50 cm than in SISI (5.64 ± 0.93 kg m^{-2}) (Fig. 3).

3.2.2 Landscape units

Topsoil SOCS (0–25 cm) in LU2 and LU3 are 10% respectively 23% lower in RUSS compared to SISI, where LU1 and LU4 are around 30% lower than in RUSS. Within 25–50 cm, SOCS are similar with around 3 kg m^{-2} and 4 kg m^{-2} in LU2 respectively LU4 in both study areas. Within 100–200 cm SOCS are 20–59% higher in all LUs than in RUSS (Fig. 3).

3.2.3 Aspect

In both study areas, SOCS is lowest on east-facing locations. SOCS on southeast-facing locations is 59% higher in SISI than in RUSS where SOCS are 54% higher on west-facing locations compared to SISI. Within all depth increments, SOCS is higher on south-facing locations in SISI than in RUSS. In RUSS, SOCS are higher on west-facing locations within the depth increments of the uppermost 100 cm but lower within 100–200 cm compared to SISI (Fig. 4).

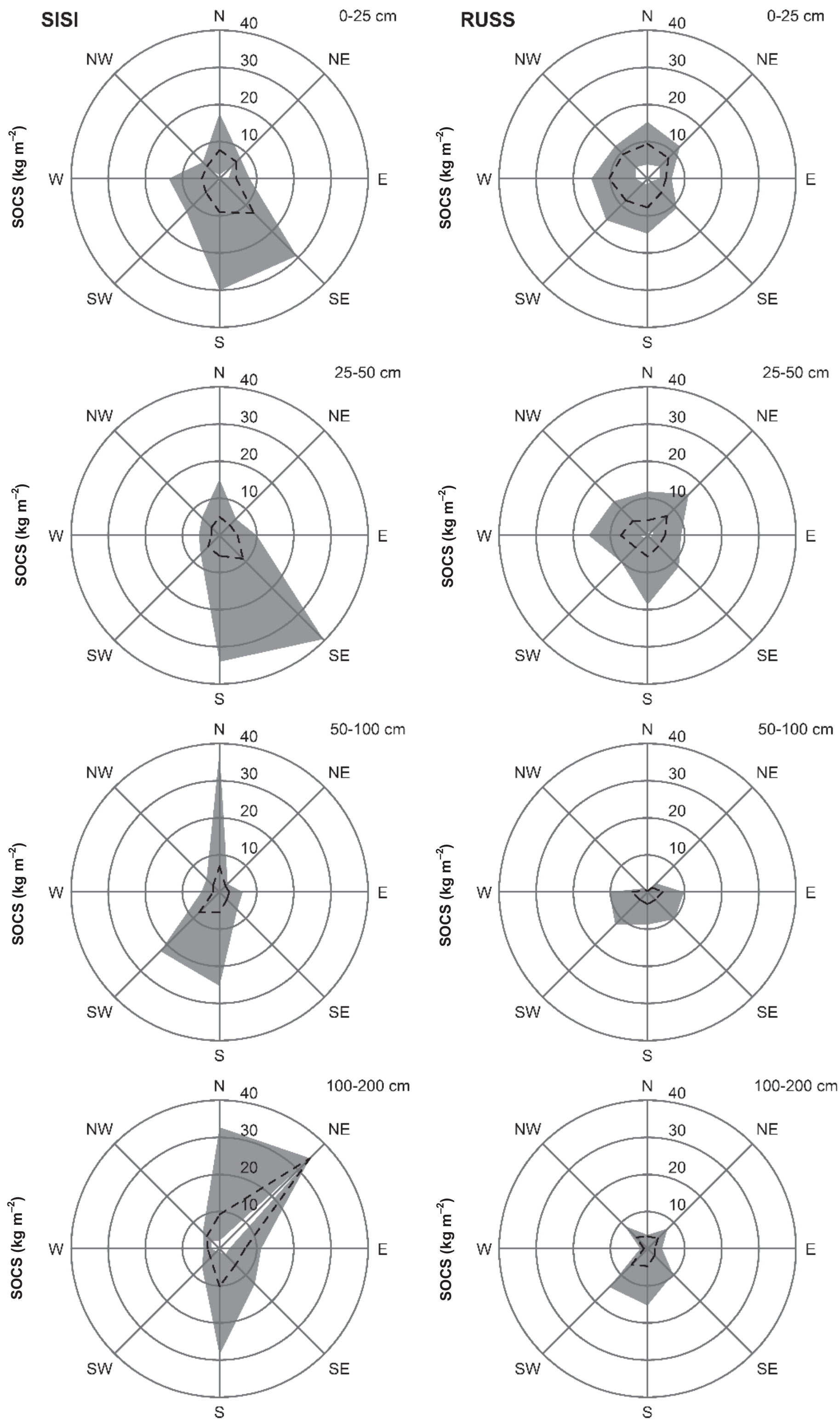

Figure 4: Variation in SOCS (mean: dashed line) related to the aspect in SISI and RUSS.

Table 4: Descriptive statistics of SOC content, BD, SOCS, soil moisture and AL thickness in SISI and RUSS (value with "< " indicates the detection limit).

Study area	Soil characteristic	Depth (cm)	*n*	Min	Mean ± SD		Max
SISI (coast)	SOC content (%)	0–25	74	0.28	6.14	± 7.00	28.96
		25–50	73	< 0.02	2.09	± 2.69	14.37
		50–100	66	< 0.02	0.82	± 1.00	5.65
		100–200	42	0.20	1.02	± 0.98	4.30
	BD (g cm^{-3})	0–25	8	0.43	0.65	± 0.30	1.23
		25–50	8	1.02	1.17	± 0.08	1.33
		50–100	8	1.13	1.34	± 0.09	1.45
		100–200	8	1.38	1.42	± 0.09	1.68
	SOCS (kg m^{-2})	0–25	74	0.34	7.85	± 7.77	30.05
		25–50	73	< 0.02	5.25	± 7.72	39.52
		50–100	66	< 0.02	4.42	± 6.18	38.10
		100–200	42	0.87	7.91	± 8.10	34.48
	Soil moisture (%)	0–5	74	0.70	26.80	± 23.48	92.60
	Lower limit of AL (cm)	0–200	17	4.00	70.00	± 42.70	144.00
		>200	57	–	–	–	
RUSS (ice margin)	SOC content (%)	0–25	66	0.46	3.23	± 1.45	6.27
		25–50	65	0.20	2.41	± 2.05	9.44
		50–100	56	< 0.02	0.97	± 1.30	7.29
		100–200	33	< 0.02	0.54	± 0.67	3.47
	BD (g cm^{-3})	0–25	8	0.84	0.97	± 0.08	1.10
		25–50	8	0.82	1.12	± 0.18	1.39
		50–100	8	0.83	0.99	± 0.30	1.40
		100–200	8	1.06	1.24	± 0.22	1.75
	SOCS (kg m^{-2})	0–25	66	1.01	7.86	± 3.74	15.79
		25–50	65	0.58	5.41	± 4.24	18.75
		50–100	56	< 0.02	2.82	± 3.13	12.32
		100–200	33	< 0.02	3.74	± 3.97	15.33
	Soil moisture (%)	0–5	66	0.70	8.33	± 7.08	25.50
	Lower limit of AL (cm)	< 200	37	6.00	53.00	± 28.09	142.00
		> 200	29	–	–	–	

4 Discussion

4.1 Local scale variations in SOCS

4.1.1 Vegetation units

Generally, topsoil SOCS are controlled by vegetation cover because most Arctic plants root within the upper 25–30 cm (*Iversen* et al., 2015). Vegetation varies in its spatial distribution and portions affecting the spatial distribution of SOCS in Arctic environments (*Elberling* et al., 2008b; *Horwath Burnham* and *Sletten*, 2010; *Palmtag* et al., 2015; *Siewert* et al., 2015; *Wojcik* et al., 2019). In SISI, VEG1 predominantly covers west- and northwest-facing locations where plant growth might be restricted by constant onshore winds and high direct solar radiation. For VEG1, SOCS are lowest due to low accumulation rates of SOC in coastal regions in West Greenland (*Jensen* et al., 2006). Besides, organic material is relocated from steep slopes covered by VEG1 to depressions and flat areas covered by VEG4. Soils covered by VEG4 have thick and humus rich topsoil horizons because of dense rooting, low decomposition rates and a constant accumulation of soil organic matter (SOM) under moist soil conditions due to oceanic climate conditions (*Stäblein*, 1977; *Jensen* et al., 2006). Similar SOCS for VEG2 and VEG3 result from similar mechanisms of SOC storage (*Petrenko* et al., 2016). However, SOCS are highest for VEG3, which is sparsely occurring and not characteristic for coastal areas in West Greenland (*CAVM Team*, 2003). In SISI, SOCS with combined shrub tundra vegetation (VEG2 and VEG3: 10.57 ± 6.33 kg m^{-2}) correspond to findings by *Bradley-Cook* and *Virginia* (2016) of 10.20 kg m^{-2} with comparable vegetation in coastal West Greenland.

In RUSS, accumulation of SOM in the topsoil is mainly caused by the incorporation of leaf remains of *Salix glauca* (*Ozols* and *Broll*, 2003), the dominant species of VEG3. Under dry soil conditions decomposition of SOM is lower and so SOCS are higher for VEG3 than VEG2. In contrast, decomposition of SOM is also limited by high soil moisture conditions in depressions, flat and bankside areas predominantly covered by VEG4. Similar SOCS for VEG2 and VEG4 correspond to findings of *Petrenko* et al. (2016) detecting no significant differences in SOCS in 0–50 cm between graminoid and shrub vegetation at the ice margin in West Greenland. Dry katabatic winds and low precipitation rates during the growing season influence the growth of VEG1 and reduce biomass productivity on wind-exposed areas as well as the incorporation of organic matter into the soil (*Ozols* and *Broll*, 2003).

4.1.2 Landscape units

In SISI, topsoil SOCS vary spatially with different LUs. LU3 includes the foot slope of a large catchment area in the north of SISI into which SOC is transported by overland and subsurface flow (*Stäblein*, 1977). At coastal area of West Greenland cryoturbation processes were found as a characteristic phenomenon (*Stäblein*, 1977; *Jensen* et al., 2006). Deep thawing of soils during summer fosters vertical relocation of SOC *via* cryoturbation processes and results in high SOCS at 50–100 and 100–200 cm at all landscape units in SISI. In LU4, SOCS are highest at 50–100 cm, which might be connected a thick active layer since the isolating effect of sites with low-growing vegetation is less than on sites with shrub vegetation leading to deep thawing and relocation of SOC in LU4. Besides cryoturbation, SOCS can also be high in the subsoil caused by buried organic material which was deposited or covered by slope processes related to various topographic positions within different landscape patterns (*Palmtag* et al., 2015, 2018; *Wojcik* et al., 2019).

In RUSS, a spatial variation in SOCS can be related to the varying impact of local climate conditions. Climate conditions at the ice margin in West Greenland commonly have dry and cold katabatic winds blowing from the Greenland Ice Sheet to the west. These dry winds increase evapotranspiration and prevent growth of vegetation (*Cappelen* et al., 2001), especially at wind-exposed areas like moraine crests with east-facing upper slopes (LU2). Since tall shrub tundra has highest SOCS (Fig. 3), but does not occur in LU2, SOCS are the lowest in all depth increments in LU2. Lowest SOCS within 0–25 cm in LU2 in RUSS (5.66 ± 3.00 kg m^{-2}) correspond to findings in the Umimmalissuaq valley, located at the ice margin 20 km to the south of RUSS, where SOCS from 0–30 cm are also lowest with 6.01 ± 2.49 kg m^{-2} at crest positions with similar environmental conditions as in LU2 in RUSS (*Henkner* et al., 2016).

A common geomorphological feature are terminal moraines oriented perpendicular to the dominant wind direction in RUSS. These moraines reduce the negative effects of katabatic winds on the vegetation cover on leeside locations leading to higher SOCS within 0–25 cm in LU1, LU3, and LU4. Hence, landscape conditions affect the variation in SOCS in RUSS in 0–25 cm by negative effects of katabatic winds to plant growth, which result in higher SOCS on leeside positions than in wind-exposed areas in RUSS.

Including all depressions and lake-surrounding areas, LU1 includes generally very moist and wet soil conditions, which explain highest SOCS within 0–25 cm (9.40 ± 3.70 kg m^{-2}) and 25–50 cm (8.11 ± 3.97 kg m^{-2}). In LU1, highest SOCS also occur in 50–100 cm and 100–200 cm, which can be linked to organic matter buried by lake sediments from alternating lake water levels during the Holocene (*Willemse* et al., 2003) or by relocated sediments (*Palmtag* et al., 2018). Lower SOCS in LU4 than in LU1 can be explained by generally dry hillslope areas in LU4 and the availability of oxygen and the microbial activity is higher causing higher decomposition of SOC (*Elberling* et al., 2004).

4.1.3 Aspect

In SISI, SOCS are lowest on west-facing (SW, W, NW) locations. Due to high solar energy input on northwest-facing and west-facing locations, high decomposition rates benefit from warm soil conditions resulting in low SOCS (*Elberling* et al., 2004). On east-facing locations direct solar radiation is low caused by frequently occurring fog until noon (*Cappelen* et al., 2001). After the fog has lifted, the sun stands in the southern sky, causing lower direct solar radiation on east-facing locations than on west- and northwest-facing locations. In SISI, SOCS are highest on south-facing locations because of better growing conditions than on north-facing locations. Generally, south-facing locations have a high solar energy input and higher water availability caused by the water discharge from a large catchment area in the north of SISI. These particular natural conditions result in better plant growth and reduced decomposition processes of SOCS on south-facing locations with moist soil conditions.

In RUSS, SOCS on east-facing and west-facing locations are related to katabatic winds constantly blowing from the Greenland Ice Sheet. Therefore, lowest SOCS at 0–25 cm were found on east- and southeast-facing locations as biomass production and input of organic matter into the soil is restricted by these winds (*Henkner* et al., 2016). In contrast, west- and northwest-facing locations have highest SOCS within 0–25 cm because these leeside locations are favored by shrub vegetation responsible for high SOCS (*Ozols* and *Broll*, 2003; *Petrenko* et al., 2016). The same reason applies for south and southwest-facing locations with higher SOCS compared to east-facing and northeast-facing locations. According to the findings of *Henkner* et al. (2016) in the

Umimmalissuaq valley, higher SOCS on north-facing than on south-facing locations result from higher mineralization rates due to higher soil temperatures and lower soil moisture content on south-facing locations. Wind exposed crest positions in the Umimmalissuaq valley also show lowest topsoil SOCS (6.01 ± 2.49 kg m^{-2}, 0–30 cm) comparable to east- and southeast-facing locations in RUSS (5.17 ± 2.16 kg m^{-2}, 0–25 cm). Also, SOCS on south- and southwest-facing locations, which are less influenced by katabatic winds, are similar between RUSS (8.04 ± 4.20 kg m^{-2}, 0–25 cm) and the Umimmalissuaq valley (8.35 ± 4.16 kg m^{-2}, 0–30 cm; *Henkner* et al., 2016).

North-facing slopes in RUSS have highest SOCS. Differences in SOCS between RUSS and the Umimmalissuaq valley might result from different calculation approaches for SOCS as *Henkner* et al. (2016) did not account for the volume and density of the coarse fraction being important for determining SOCS (*Tarnocai* et al., 2009). The Umimmalissuaq valley and RUSS are both located in valleys with comparable environmental conditions including elevation (about 200 m asl), orientation (southeast to northwest), vegetation (dominant species), distance to the ice margin (< 10 km), and climate conditions (*Cappelen* et al., 2001; *Henkner* et al., 2016). Thus, comparable environmental conditions on a local scale are reflected by similar SOCS at comparable topographic positions in ice marginal areas in West Greenland. In several locations close to the ice margin in RUSS, higher SOCS were found in 25–50 cm because of buried dark and organic-rich horizons potentially representing Holocene palaeosols (*cf Müller* et al., 2016).

4.2 Regional scale variations in SOCS

On average, SOCS in 0–25 cm and 25–50 cm are similar in both study areas which correspond generally to large scale estimations showing no differences in SOCS between the coastal and the ice margin area. However, SOCS are lower on average and have larger ranges in areas at the coast and at the ice margin than we found between SISI and RUSS (*Jones* et al., 2009; *Hugelius* et al., 2014; *Köchy* et al., 2015). *Hugelius* et al. (2014) found SOCS with 0.1–5 kg m^{-2} within 0–30 cm, which is lower than the average SOCS in both study areas (SISI: 7.85 ± 7.77 kg m^{-2}; RUSS: 7.86 ± 3.74 kg m^{-2}). The ranges of the SOCS within 0–25 cm in SISI and RUSS are sixfold respectively threefold the range of estimated SOCS within 0–30 cm (*Hugelius* et al., 2014).

On average, SOCS in 50–100 cm and 100–200 cm are 1.60 kg m^{-2} and 4.17 kg m^{-2} higher in SISI than in RUSS (Tab. 4). These differences can be explained by cryoturbation processes which are characteristic at the coast in SISI (*Stäblein*, 1977) but are not present at the ice margin in RUSS in West Greenland (see *Petrenko* et al., 2016). Additionally, higher maximum values of SOCS in all depth increments in SISI compared to RUSS might result from the different landscape ages. Soil formation lasted 3,000 years longer and could accumulate more SOM at the coast at Sisimiut compared to the ice marginal areas in West Greenland around Kangerlussuaq (*Bradley-Cook* and *Virginia*, 2016), which was deglaciated around 6.8 ka ago (*e.g.*, *Levy* et al., 2012).

However, differences in SOCS within 0–100 cm and 100–200 cm between SISI and RUSS are in contrast to large scale estimations mentioned above. *Hugelius* et al. (2014) found similar SOCS with 5–15 kg m^{-2} in 0–100 cm and 100–200 cm, whereas *Jones* et al. (2009) suggest SOCS from 0–100 cm with 9–15.9 kg m^{-2} and *Köchy* et al. (2015) with 10 kg m^{-2}. In both study areas, SOCS within 0–100 cm (SISI: 16.87 ± 14.79 kg m^{-2}; RUSS: 15.49 ± 8.75 kg m^{-2}) are slightly higher than estimated by *Jones* et al. (2009) and *Hugelius* et al. (2014) within the first 100 cm and around 30% higher than the results by *Köchy* et al. (2015). In 100–200 cm, the wide range of SOCS in SISI represents the high variation of SOCS in the study area and is with 33.61 kg m^{-2} twice the estimated range of 5–15 kg m^{-2} (*Hugelius* et al., 2014), which corresponds to the range of SOCS in RUSS (15.33 kg m^{-2}).

Such general estimations of SOCS have a tendency to be uncertain, caused by the underlying datasets containing data gaps, which have to be filled mathematically. Additionally specific soil characteristics may have a high uncertainty, *e.g.*, the bulk density, which is a crucial parameter for the calculation of SOCS (*Tarnocai* et al., 2009; *Hugelius* et al., 2014; *Köchy* et al., 2015; *Ping* et al., 2015). Furthermore, the available data may have been not representative for regions, which counts particularly for Greenland (*Hugelius* et al., 2014; *Köchy* et al., 2015).

The SOCS in SISI and RUSS are higher compared to northern coastal regions in Greenland. At Zackenberg in Northeast Greenland, SOCS from 0 to 50 cm are with 11.00 ± 1.5 kg m^{-2} (*Elberling* et al., 2004) lower than in SISI with 13.18 ± 12.82 kg m^{-2} (0–50 cm). On Thule peninsula in Northwest Greenland, SOCS are 6.10 kg m^{-2} from 0 to 100 cm (*Horwath Burnham* and *Sletten*, 2010) and 6.7 kg m^{-2} from 0 to 60 cm on Disko Island (*Jensen* et al., 2006). Differences in SOCS may be caused by colder climate conditions in the north. Further, it has to be noted that other study areas as mentioned above cover also vegetation and landscape patterns with lower SOCS, which do not occur in our study areas. For a better understanding of differences in SOCS between SISI and RUSS on the regional scale, differences in the controlling factors between the coast and the ice margin are pointed out in the following.

4.2.1 Vegetation units

Differences in vegetation between SISI and RUSS correspond to the bioclimatic zonation of the Circumpolar Arctic Vegetation Map indicating a higher net annual production at the ice margin compared to the coast (*CAVM Team*, 2003). This suggests the possibility of higher SOCS in RUSS than in SISI. However, SOCS are generally around 1.40 kg m^{-2} (0–25 cm) higher within the same vegetation unit (VEG2, VEG3, VEG4) in SISI than in RUSS, except for VEG1 where SOCS are 0.30 kg m^{-2} (0–25 cm) lower in SISI. Oceanic climate suggests better growing conditions in SISI than in RUSS where plant growth is limited by dry climate at the end of the growing season. With increasing mean summer temperatures and decreasing mean annual precipitation from the coast towards the ice margin (*Cappelen* et al., 2001), the decomposition of SOM in Greenland is higher under drier and warmer conditions (*Elberling* et al., 2004; *Jensen* et al., 2006). Higher SOCS in the uppermost 20 cm in coastal areas compared to lower SOCS in inland areas with same vegetation cover are related to the deglaciation history (*Bradley-Cook* and *Virginia*, 2016). In summary, this results in higher SOCS in SISI than in RUSS within the same vegetation unit.

Besides effecting the amount of SOCS in SISI and RUSS in different ways, regional climate conditions also influence the spatial distribution of SOCS within both study areas. There is a significant relation between vegetation and SOCS at 0–25 cm in RUSS but not in SISI. Due to higher mean annual precipitation at the coast, SOC is relocated by overland and interflow processes (*Stäblein*, 1977), whereas only little effect of them is noticeable on the spatial distribution of SOC at the ice margin. Therefore, SOCS are result of the *in situ*-production and incorporation of organic material into the soil in RUSS.

4.2.2 Landscape units

Corresponding landscape units between both study areas are characterized by the same landscape conditions, but have different SOCS caused by different climate conditions between the coastal and the ice margin area. In general, SOCS at 0–25 cm are higher in RUSS than in SISI as shrub growth is favored at wind-sheltered areas leading to high SOCS (LU1, LU3, and LU4) in RUSS. Katabatic winds negatively affect SOCS in LU2 only in RUSS, which results in higher SOCS within 0–25 cm in LU2 in SISI. Induced by higher mean annual precipitation at the coast, SOC is relocated by overland flow resulting in higher SOCS in LU3 in SISI than in RUSS, where overland flow is limited due to the dry climate at the ice margin.

4.2.3 Aspect

In both study areas, SOCS are lowest on east-facing locations as plant growth is negatively affected by the following climate conditions: increased evapotranspiration by katabatic winds in RUSS and reduced direct solar radiation by morning fog in SISI. The leeside areas of terminal or lateral moraines favor the growth of VEG2 and VEG3 in RUSS, west-facing locations in SISI represent locations with restricted plant growth by coastal west winds. Thus, SOCS on west-facing locations are higher in RUSS than in SISI.

4.3 The role of controlling factors to describe the spatial distribution of SOCS in West Greenland

SOCS have a high spatial variation in West Greenland on both the local and the regional scale. The chosen controlling factors differ in their ability to describe the variation in SOCS on both scales in different ways. We ranked the controlling factors by their potential (+++ high; ++ medium; + low) to account for the variation in SOCS (Tab. 5). The ranking is expert-based on comparing the potential of each unit to be unique according to the used classification scheme. A high potential means each unit represents a specific range of the SOCS distribution within the study areas (local scale) and the ranking is also stable over both study areas (regional scale) (*cf* Figs. 3 and 4).

Table 5: Potential of controlling factors to describe the variation in SOCS on the local and the regional scale (VEG: vegetation, LU: landscape unit, ASP: aspect, +++ high potential, ++ medium potential, + low potential).

	Local scale	Regional scale
VEG	+++	+++
LU	+	++
ASP	+++	+++

Vegetation units have a great potential to describe both local and regional scale variation in SOCS, because vegetation incorporates to a certain extent local distribution patterns of wind, geomorphology and insolation as well as their differences between the coast and the ice margin on the regional scale. However, topsoil SOCS are similar for VEG2 and VEG4, which results from water driven relocation of SOC in SISI. The negative effect of katabatic winds on SOCS is best described by ASP, which can be explained by the continental climate conditions in RUSS. In addition, vegetation units have distinct differences in SOCS for all depth increments below 25 cm. Therefore, VEG is highly suitable to describe the variation in SOCS (+++) on the local scale. On the regional scale, SOCS have similar distribution patterns for different VEG but differences in the amount of SOCS between SISI and RUSS. This accounts for VEG a high potential to describe the variation in SOCS (+++) on the regional scale as well.

In general, landscape and landform classifications are common approaches to address the horizontal and vertical distribution of SOCS (*Siewert* et al., 2016; *Palmtag* et al., 2018; *Wojcik* et al., 2019). Further, such classifications are suitable to represent local patterns like accumulation areas with additional input of SOC (as in SISI) or lower SOCS on convex shaped moraines (as in RUSS). In addition, LUs comprise the influence of local climate conditions in RUSS. However, in this study, LUs have low potential (+) to describe the variation in SOCS on the local scale. Representing comparable geomorphological features between SISI and RUSS, LUs account for the effect of different climate conditions and the variations in SOCS on the regional scale (++) by different amounts of SOCS of the related LU.

ASP performs high with both scales (+++). It represents locally strong differences in solar radiation between north- and south-facing and east- and west-facing topographic positions. Regionally, ASP describes climate conditions between the coast and the ice margin, *i.e.*, mainly different wind systems.

Our results correspond to the findings of other studies using landform classification approaches in Arctic environments (*Elberling* et al., 2008b; *Henkner* et al., 2016; *Siewert* et al., 2016; *Palmtag* et al., 2018; *Wojcik* et al., 2019) and show that both LU and ASP yield additional relevant information to analyze and understand the spatial distribution of SOCS in West Greenland. Both, LU and ASP reflect specific environmental conditions on the local scale within the study areas and on a regional scale differences between the study areas. Most importantly, ASP has a high potential to describe the variations in SOCS on both scales, which is not the case for LUs. Thus, to have the best description of the variations in SOCS, we recommend to use vegetation units and the aspect. Vegetation extracted from remote sensing data provides the advantage to describe the variations in SOCS with a high resolution across large areas. In addition, the aspect can be taken from digital elevation models (DEM) by using various GIS software.

5 Conclusions

This study presents new data of SOCS from two different regions of West Greenland, a coastal (SISI, oceanic climate) and an ice marginal (RUSS, continental climate) area. We focused on three controlling factors (VEG, LU, ASP) to describe the variation in SOCS on two different scales (local, regional). The local scale reflects the spatial variation in the controlling factors over short distances within each study area and the regional scale the different climate conditions between both study areas.

On a local scale, VEG and ASP have the highest potential to describe the distribution of SOCS in both study areas. SOCS vary spatially and vertically with different vegetation pattern, landscape units and aspect. In both study areas, SOCS within 0–25 cm are highest with tall shrub tundra (VEG4) and lowest with dwarf shrub heath tundra (VEG1) covering predominantly areas exposed to local wind patterns or areas with a high solar radiation input. Both are limiting plant growth and the accumulation of SOC. Except for VEG1, SOCS are around 1.40 kg m^{-2} higher in SISI than in RUSS due to effect of different climate conditions.

On the regional scale, also VEG and ASP have the highest potential to describe the distribution of SOCS. In both study areas, the mean SOCS are similar from 0–25 cm and 25–50 cm. Due to oceanic climate conditions, cold and moist soil conditions support accumulation of soil organic matter in SISI. In contrast, we assume production and decomposition of soil organic matter to increase due to warmer and drier conditions in RUSS. Mean SOCS within 50–200 cm are up to 53% higher in SISI than in RUSS. Coastal climate conditions in SISI foster vertical relocation of soil organic carbon by cryoturbation processes, which plays in contrast a minor role to the vertical distribution of SOCS in RUSS. Additionally, a longer period of soil formation at the coast—related to earlier deglaciation of the landscape—results in a wider range of SOCS being two times higher in all depth increments (0–25, 25–50, 50–100, 100–200 cm) in SISI than in RUSS.

Generally, SOCS are up to six times higher at 0–25 cm, up to 30% higher at 0–100 cm and two times higher in 100–200 cm in both study areas in comparison to existing large scale estimations. This may be caused by sparse and unequal distributed soil data available for large scale estimations resulting in a high uncertainty. However, it should be considered that our study was carried out in two small study areas (around 2 km^2 each) and therefore we propose to add further representative areas for a comprehensive comparison on a larger scale, *e.g.*, West Greenland.

The applied controlling factors VEG, LU, and ASP are suitable to examine horizontal and vertical distribution of SOCS on both the local and the regional scale. Our results show that vegetation in combination with additional environmental factors such as landscape units and aspect better explain the variation in SOCS on both scales. However, we recommend using at least the aspect together with vegetation, because this yielded excellent results to determine the variation in SOCS in alpine zones as, *e.g.*, in West Greenland on both scales.

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