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Effect of terrain characteristics on soil organic carbon and total nitrogen stocks in soils of Herschel Island, western Canadian Arctic

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Abstract

Areas underlain by permafrost, store large amounts of organic matter, which may become a source of greenhouse gases upon permafrost degradation. Permafrost landscapes can be affected by different disturbances. We analysed the influence of terrain and geomorphic disturbances (e.g. soil creep, active layer detaching, gullying, slumping, fluvial accumulation) on soil organic carbon (SOC) and total nitrogen (TN) storage using 11 permafrost cores from Herschel Island. Our results indicated a strong correlation between SOC storage and topographic wetness index. Undisturbed sites stored majority of SOC and TN in the upper 70 cm. Sites characterised by mass wasting showed significant SOC depletion and soil compaction, while accumulation sites store SOC and TN along the whole core. The impact of geomorphic disturbance should be considered when estimating SOC stores, and further research about slow, continuous mass movements is required. We upscaled SOC and TN to estimate total stocks using ecological units determined from vegetation composition, slope angle, and geomorphic disturbance regime. The ecological units were delineated with supervised classification based on RapidEye multispectral satellite imagery and slope angle. Mean SOC and TN storage for the uppermost 1 m on Herschel Island are 34.8 kg C m^{-2} and 3.4 kg N m^{-2}.

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1 Introduction

Landscapes underlain by permafrost are favourable environments for organic matter accumulation (Hobbie et al. 2000). Annual ground temperatures below 0ºC coupled with impeded drainage result in low organic matter degradation rates and cryoturbation transport of organic matter into lower horizons, leading to long-term carbon storage (Hobbie et al., 2000, Bockheim, 2007). As a consequence, permafrost areas have acted as organic carbon sinks during recent geological times and large quantities of organic matter have accumulated in the subsurface (Hugelius et al., 2014).

Arctic air and ground temperatures have increased over the last half century, leading to enhanced permafrost thaw and deepening of the active layer (Romanovsky et al. 2010). This warming could, in turn, result in the transformation of carbon sinks into sources (Schuur et al., 2009) and the release of old soil carbon into the atmosphere as carbon dioxide or methane (Zimov et al., 2006). Greater concentrations of these two greenhouse gases in the atmosphere and a further warming of air temperatures could lead to a process termed "permafrost carbon feedback" (Schaefer et al., 2014).

Nitrogen is considered a limiting nutrient in northern ecosystems (Shaver and Chapin, 1980); it plays an important role in ecosystems and carbon cycling (Harden et al., 2012) and is also made available during organic matter decomposition (Meyers, 1994). Activated nitrogen-rich organic compounds can be subject to nitrification and denitrification, which can produce nitrous oxide (N_2O), another important greenhouse gas (Ciais et al., 2014). Organic carbon and nitrogen can also be released directly to the marine realm through coastal erosion and river discharge (Lantuit et al., 2012, Vonk et al., 2012). Increased release of both carbon and

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nitrogen from permafrost soils due to thaw could have important impacts on Arctic terrestrial, aquatic, and marine ecosystems (Jones et al., 2005; Frey et al., 2007).

Greenhouse gas and lateral organic carbon and nitrogen fluxes originating from thawed permafrost soil organic matter have not yet been incorporated into global climate projections (Kuhry et al., 2010; Schaefer et al., 2014). Recent global estimates of total soil organic carbon stocks in permafrost areas range between 1100 and 1500 Pg, and around 472 Pg for the 0-1 m depth only (Tarnocai et al., 2009; Hugelius et al. 2014). There is no comparable circum-Arctic estimation for nitrogen stocks. The adequate incorporation of carbon and nitrogen stores and fluxes into climate projections is hindered by uncertainties in the amount of soil carbon in the soil profile (Koven, 2013; Burke et al., 2013). The distribution of soil organic carbon (SOC) is also highly heterogeneous across the landscape, making modelling efforts sensitive to averaging strategies used in baseline datasets (Kuhry et al., 2010). There is, therefore, an urgent need for local, regional, and circum-Arctic inventories of SOC to mitigate these issues (Hugelius et al., 2013b).

Disturbances such as fires, permafrost thaw, and anthropogenic activities influence SOC and total nitrogen (TN) storage in permafrost landscapes (Harden et al., 2000; Turetsky et al., 2002; Myers-Smith et al., 2007; O'Donnell et al., 2011). Various geomorphic disturbances acting on the landscape depend on terrain and can also influence SOC and TN storage. Mass wasting can result in material removal and exposure of lower soil horizons to subaerial processes, which causes altered soil moisture regime and permafrost degradation (Kokelj and Lewkowicz, 1999). Grosse et al. (2011) discussed the possible effect of active layer detachments, thermal erosion gullies, and retrogressive thaw slumps (RTSs). Pizano et al.

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(2014) studied how carbon and nitrogen loss and re-accumulation are affected by RTS activity. Studies of the effect of slow mass wasting (e.g. solifluction) on SOC and TN are lacking. Geomorphic disturbance can, however, also lead to material accumulation, thereby increasing storage through riverine sedimentation (Zubrzycki et al., 2013) or peat accumulation (Botch et al., 1995). In our study, mass wasting encompasses a wide range of processes, from slow solifluction and stream gullying to rapid active layer detachments and retrogressive thaw slumping. The intensity of these processes is reflected in some of ecological units of Herschel Island (Smith et al., 1989). Thus, achieving a better understanding of the influence of geomorphic disturbances on SOC and TN stores will improve our ability to estimate changes in these stocks over time.

Circumpolar and low-resolution estimates of SOC stocks in permafrost regions were compiled by Tarnocai et al. (2009) and updated by Hugelius et al. (2013b, 2014), who upscaled pedon values to soil maps. These studies use a simple upscaling strategy, averaging values from individual pedons to landscape units such as remote-sensing-based land cover classification (Hugelius and Kuhry, 2009; Hugelius et al., 2010, 2011), geomorphic units (Ping et al., 2011; Zubrzycki et al., 2013), or units derived from the Normalised Difference Vegetation Index (NDVI) (Horwath Burnham and Sletten, 2010). In contrast to estimations of SOC stocks, regional studies of TN stocks in permafrost regions are scarce and were compiled only by Ping et al. (2011), Harden et al. (2012) and Zubrzycki et al., (2013).

In order to better estimate changes in carbon and nitrogen fluxes caused by permafrost disturbance and thaw, more accurate storage assessments and a better understanding of the role of different disturbances are required.

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This study addresses these gaps by testing the following hypotheses:

1) Terrain significantly influences SOC and TN storage on Herschel Island.

2) Mass wasting in permafrost environments significantly reduces SOC and TN storage.

The aim of this study is to improve our knowledge about processes affecting SOC and TN storage in permafrost environments. Our objectives are (1) to compile a high-resolution estimate of SOC and TN storage for Herschel Island (Yukon Territory, Canada), a location known for a diverse terrain and large number of mass movements (Lantuit and Pollard, 2008) and (2) to assess the influence of terrain and geomorphic disturbance on SOC and TN storage.

2 Study Area

Herschel Island is located in the Beaufort Sea off the northwestern Yukon coast (Canada), 60 km east of the Alaskan border. The island is 13 x 15 km in size and covers an area of 110 km^2 (Fig. 1). It is situated north of the Arctic Circle at 69°34'N and 138°55'W; mean annual temperature is -9°C and daily averages rise above 5°C in July and August (Burn, 2012). Yearly precipitation is between 150 and 200 mm. Due to strong winds, snow is blown from higher ground and accumulates in snow beds in low-lying parts of the landscape (Burn, 2012). Herschel Island is a push moraine that was formed by the Laurentide ice sheet progression (Bouchard, 1974; Fritz et al., 2012). The island is therefore made of unconsolidated and mostly fine-grained marine sediment and is characterised by abundant massive ice of glacial origin (Bouchard, 1974; Pollard, 1990; Fritz et al., 2011). Permafrost is continuous with mean annual ground temperature of -8 °C at zero amplitude depth at Collinson Head. Active layer depths normally range between 40 and 60 cm depending on topography (Burn and Zhang,

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2009).

Herschel Island rises to a maximum height of 180 m a.s.l. Its undulating topography is cut by numerous valleys and gullies. The walls of these gullies are often devoid of vegetation and are undergoing strong geomorphic disturbance. A number of the gullies end in alluvial fans. Wet terrain with polygonal ground is present on flatter ground and in enclosed depressions. Slopes are characterised by mass movements ranging from slow solifluction to rapid active layer detachments (Fig. 2). Beaches are characterised by high bluffs or spits. The coastline is often disturbed by RTSs that form because ground-ice-rich headwalls wear back laterally (Lantuit et al., 2012). The island coasts are characterised by high rates of coastal erosion (Lantuit and Pollard, 2008).

Soils on Herschel Island were classified according to the Canadian system of soil classification (Canada Soil Survey Committee, 1978). Organic Cryosols predominate and other soil types are present only on beaches and spits which are not underlain by near surface permafrost (Smith et al., 1989). The most typical subtypes are Turbic Cryosols, characterised by cryoturbation, and Static Cryosols, characterised by recent disturbance. Soils that are not underlain by permafrost are either Regosols or Brunisols (Smith et al., 1989). The general vegetation type on Herschel Island is lowland tundra composed of various vegetation types (Table 1) (Smith et al., 1989; Myers-Smith et al., 2011).

Smith et al. (1989) conducted an extensive soil and vegetation survey on Herschel Island and defined eight ecological units (Table 1). These ecological units reflect the vegetation, but also soil characteristics and geomorphologic disturbance. We used these units as the basis for SOC

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and TN content upscaling and site grouping according to geomorphic disturbance (see section 3.5). The names of the units defined in the publication are based on local landmarks or fauna. We adapted these unit names to landscape and terrain characteristics in order to enable comparison with units from other areas in the Arctic with similar characteristics.

3 Methods

3.1 Field work and sampling

In July 2013, we cored 11 locations (Table 2) selected to be representative of each of the ecological units (Table 1). At each coring location, a detailed terrain and vegetation survey was undertaken to characterise the surface. A pit was dug until the thaw depth was reached. Cores were drilled to a depth of 60 – 250 cm below the surface with a Snow, Ice, and Permafrost Research Establishment (SIPRE) permafrost coring auger barrel drill (manufactured in Jon's Machine Shop) with an inner diameter of 7.5 cm and equipped with a Stihl BT 121 engine. Where thaw depth exceeded 70 cm, a pit was dug and no permafrost core was taken because of the difficulty of digging and setting up the coring equipment. We drilled at least one core in each ecological unit, ten cores and two pits in total. The uppermost metre of the pit or core was sampled every 10 cm; below one metre we sampled every 20 cm. Sampling depths were adapted to visible changes in facies or cryostructure. We obtained 7.5x7.5x5 cm samples from the active layer. Permafrost core samples were 5 cm thick and 7.5 cm in diameter.

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3.2 Laboratory analyses

The 128 samples were weighed to determine wet weight, freeze dried at -20 °C in vacuum, then weighed again for dry weight, ground, mixed and milled for elementary analyses, and then subsampled for further analyses. Samples were then separately analysed for carbon and nitrogen content in an Elementar vario EL III and for total organic carbon content using an Elementar vario MAX C manufactured by Elementar Analysensysteme GmbH.

3.3 Ecological unit mapping

Ecological units were mapped from remotely-sensed imagery and a digital elevation model (DEM) using a supervised classification. These units were defined based on terrain properties, soil types, and vegetation, and thus are suitable for the study of soil properties in relation to geomorphic processes. A cloud-free and almost snowpack-free RapidEye satellite acquisition on August 15th 2010 was selected to map the units. The RapidEye image is multispectral and has a horizontal resolution of around 6.5 m at nadir. The image was georeferenced based on ground control points taken from Lantuit and Pollard (2008) and orthorectified using a DEM derived from an IKONOS stereopair. The DEM itself was resampled from 2 m resolution to 6.5 m resolution with cubic convolution to fit to the resolution of the RapidEye image. Small artefacts (parallel stripes) were removed from the DEM dataset using a 4x4 round average filter. Preliminary results showed that SOC content correlates well with slope angle and for this reason it was added to the classification. The slope angle layer at 6.5 m resolution was calculated from the DEM. An atmospheric correction (Atmospheric and Topographic Correction (ATCOR) module in PCI Geomatica 2013) (Richter, 1996) was applied to the RapidEye image to calculate the surface reflectance values and remove the effects of low sun angle and shading.

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Areas surveyed in the field were used as training units for the supervised classification. The terrain was inspected visually for vegetation and terrain properties to correctly assign the sites to the ecological units. The area boundaries were mapped in the field with a handheld Garmin Etrex H GPS. We added additional areas that we delineated on the basis of satellite imagery for the areas that had been identified during helicopter surveys (spits, alluvial fans, and polygons). In total, 21 areas were used as training units for supervised classification. An additional training unit was added to identify water bodies and separate them from the classification results. A slope layer was added as a new input band to improve the classification results.

The maximum likelihood supervised classification of the RapidEye image and slope angle added as an additional layer was performed in Exelis ENVI 5.0. The result was post-processed by sieving in ENVI and by using a 4x4 circle majority filter and boundary-clean tools in ESRI ArcGIS 10.1 to remove isolated pixels and incorporate small unit areas into adjacent and prevalent units. The classification accuracy was assessed using ground truth points. We used coring locations and vegetation survey locations from the previous fieldwork of Myers-Smith et al. (2011). Additionally, we used ground truth points collected from other parts of the island by previous expeditions (e.g. Lantuit et al., 2012). Photos and vegetation data collected at the survey sites during these expeditions were inspected and assigned to an ecological unit. A total of forty ground truth points were collected to assess the classification accuracy (Fig. 2).

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3.4 Upscaling of SOC and TN contents

Contents of SOC and TN were calculated using gravimetric contents of total organic carbon (TOC) and TN in the samples. The dry bulk density was calculated using the dry weight and the volume of samples. Volumetric TOC and TN contents (kg C m^{-2} and kg N m^{-2}, respectively) were then calculated for one centimetre sample thickness (cm m^2) using the following equations:

$$SOC = cOC \times \rho \quad (1)$$

$$TN = cN \times \rho \quad (2)$$

Where cOC and cN are gravimetric contents of organic carbon and nitrogen in weight fraction and ρ is dry bulk density in g cm^{-3}. The coarse grain size fraction (particles > 2mm) was not included in the calculations because it was either absent or present in negligible amounts. SOC and TN contents from the samples were extrapolated to apply to adjacent parts of the core that were not sampled; extrapolation extended half of the distance to the next sample along the core. The total contents of SOC and TN (in kg C m^{-2} and kg N m^{-2}, respectively) in a core were calculated by summing the content of each centimetre of the core. The values were calculated for three different depth ranges: 0-30 cm (SOC 0-30cm and TN 0-30cm), 0-1 m (SOC 0-100 cm and TN 0-100 cm), and 0-2 m (SOC 0-200 cm and TN 0-200 cm). In shorter cores, the value of the lowermost sample was extrapolated downwards. Cores and pits that did not exceed one metre were J01, PG2152 and PG2162. Core PG2158 reached 143 cm. Extrapolation of SOC and TN for 0-2 m is less certain for these cores.

Core values were averaged across the cores for ecological units with more than one core; otherwise, the value of the single core was assigned to the ecological unit. These values were multiplied by cell area and numbers of cells from the classification to calculate stocks of SOC

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and TN for ecological units and for the whole island. Carbon to nitrogen (C/N) ratios for the ecological units were calculated from upscaled unit-specific SOC and TN values. We used the SOC and TN content of the uppermost metre of soil in further statistical analyses, which is standard in SOC stock quantifications (e.g. Tarnocai et al., 2009).

3.5 Assessing the role of terrain on site SOC and TN storage

We assessed the role of terrain on SOC and TN storage on Herschel Island by correlating them to environmental variables as slope, soil moisture, topographical wetness index (TWI), elevation and NDVI. Geomorphic disturbance is not a linearly measurable variable because it encompasses both accumulation and mass wasting. For this reason we divided the sites into three groups according to the prevalent geomorphic processes (Table 1); undisturbed sites (little or no accumulation or mass wasting; Slightly Disturbed Uplands and Hummocky Tussock Tundra), mass wasting (evidence of recent or past downslope movements; Strongly and Moderately Disturbed Terrain units) and accumulation (fluvial and peat accumulation; Alluvial Fans and Wet Polygonal Terrain units).

We related slope angle, elevation, moisture content, TWI and NDVI to SOC and TN storage in the uppermost metre of soil. Slope angle and elevation were measured on site. TWI and NDVI site values were extracted from raster layers (Table 2). TWI was calculated as defined by Beven and Kirkby (1979) with upslope area calculated based on D8 flow direction algorithm. TWI was calculated from the same DEM used for supervised classification. NDVI is a remote-sensing-derived proxy indicative of vegetation biomass and density and was calculated from the red and near-infrared bands of Rapid Eye imagery. The gravimetric soil

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moisture content was calculated from sample wet and dry mass on a wet soil basis and upscaled to cores using the same procedure as for SOC and TN contents. Slope angle, degree of disturbance, and elevation were measured in the field.

Shapiro–Wilk test was used to test the normality of distributions. Pearson's correlation coefficients were calculated and linear regression analysis was used to calculate R-squared values in order to estimate the amount of variance within SOC and TN that is explained by these environmental variables. P-values were corrected with “False discovery rate correction” to account for any auto-correlation effects. Significance of difference between geomorphic disturbance groups was tested with student’s t-test. All statistical analyses were calculated using the R software (version 3.0.1). The pit from the Spits and Beaches unit was not included in the correlation analysis because it is strongly influenced by marine processes that are not a subject of our study.

4 Results

4.1 Relation between geomorphic disturbance and site SOC and TN storage

Slope angle, TWI and moisture content were significantly correlated with SOC 0-100 cm (Table 3, Fig. 3). The strongest correlation was found between TWI and SOC 0-100 cm ($r = 0.79$, $p = 0.004$). Soil moisture content was also strongly positively and significantly correlated with SOC 0-100 cm ($r = 0.69$, $p = 0.020$). Slope angle was strongly negatively correlated with SOC 0-100 cm ($r = -0.68$, $p = 0.023$). Corrected p-values of significant correlations remained within the 95% confidence interval. Elevation ($r = -0.14$, $p = 0.690$) and

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NDVI (r = 0.23, p = 0.630) were not significantly correlated with SOC 0-100 cm. We found no significant correlation of any of the studied variables with TN 0-100 cm.

The comparison of means for each geomorphic disturbance group showed that SOC 0-100 cm in the mass wasting group differs significantly from undisturbed and accumulation groups (Table 4). Group means of SOC 0-100 cm do not differ significantly between the accumulation and undisturbed groups. Group means of TN 0-100 cm are not significantly different (within 95 % confidence interval) between the geomorphic disturbance groups.

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4.2 Supervised classification

According to our classification of ecological units (Table 5, Fig. 4), the Slightly Disturbed Uplands unit occupies the largest area (32 %) of the island area (110.9 km^2), followed by the Hummocky Tussock Tundra (25 %) and the Moderately Disturbed Terrain (22 %) units. The Strongly Disturbed Terrain unit occupies 11 % and the Wet Polygonal Terrain unit occupies 8 %. Spits and Beaches and Alluvial Fans units each occupy 1 % of the total area.

The comparison of our ecological classification and ground truth points showed an overall 75 % classification accuracy (Table 5) and a kappa index of 0.70. The ecological units for which all ground truth points matched the classification output were Spits and Beaches, Wet Polygonal Terrain, and Strongly Disturbed Terrain. One mismatch each occurred for the Hummocky Tussock Tundra, Alluvial Fans, and Moderately Disturbed Terrain units. Two points out of nine of the Slightly Disturbed Uplands unit were correctly classified. Ground truth points from this unit were close to the unit boundary, which could explain the lack of classification accuracy.

4.3 SOC and TN storage on Herschel Island

The mean storage of SOC 0-100 cm and of TN 0-100 cm for the entire island is 34.8 kg C m^{-2} and 3.4 kg N m^{-2} (Table 6). The highest SOC value was assigned to the Wet Polygonal Terrain unit, which contains 85 kg C m^{-2} in the uppermost metre of soil. The Hummocky Tussock Tundra, Slightly Disturbed Uplands, and Alluvial Fans units had SOC 0-100 cm of around 40 kg C m^{-2}. Slightly lower SOC values were found in the Strongly Disturbed Terrain and Moderately Disturbed Terrain units. The Spits and Beaches unit had the lowest SOC value of 5.5 kg C m^{-2}.

The TN storage generally followed SOC storage patterns, but with smaller differences. TN storage was high in Wet Polygonal Terrain and Hummocky Tussock Tundra (TN 0-100 cm was 4.6 and 4.0 kg N m^{-2}, respectively), lower in disturbed units (TN 0-100 cm 2.0 – 3.7 kg N m^{-2}), and lowest in Spits and Beaches (Fig. 5 and Fig. 6). The C/N ratio values were around 10 to 15, with the exception of the Spits and Beaches unit, which had a higher C/N ratio.

Our estimates indicate that there is 3.9 Tg of SOC and 0.4 Tg of TN in the uppermost metre of soil on Herschel Island (see Table 4). The Slightly Disturbed Uplands unit had the highest SOC and TN stocks. The Spits and Beaches unit had the lowest SOC and TN stocks. High amounts of SOC and TN were also found in the Hummocky Tussock Tundra, Wet Polygonal Terrain, and Moderately Disturbed Terrain units. Low amounts of SOC and TN were found in

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the Alluvial Fans and Spits and Beaches units, mostly because of their relatively small spatial extents. The spatial distribution of TN 0-100 cm stocks mostly followed the patterns in SOC stocks.

5 Discussion

Few studies report SOC and especially TN contents in soils of remote Arctic areas and studies estimating the influence of geomorphic disturbance regimes on SOC and TN storage are lacking. There is an acute need for high-resolution estimates of SOC and TN storage and factors determining storage (Hugelius, 2012). Our results based on 11 cores and site data showed an important effect of terrain characteristics on SOC storage. The majority of SOC 0-100 m is explained by catenary slope position. Sites that are visually affected by mass wasting show significant depletion of SOC storage. We estimate the mean storage of SOC and TN in the uppermost metre of soil on Herschel Island to be 34.8 kg C m^{-2} and 3.4 kg N m^{-2}, with total stocks in the uppermost metre of soil to be 3.9 Tg C and 0.4 Tg N. The high carbon and nitrogen storage we found on Herschel Island is comparable to estimates reported for other Arctic regions (Section 5.3).

5.1 Effects of terrain characteristics on SOC and TN storage

The strong positive correlations between TWI, slope angle and SOC 0-100 cm indicate that terrain has an important influence on SOC storage on Herschel Island. Slope angle affects soil drainage and soil moisture content, which further affects net primary production and decomposition (Birkeland, 1984). TWI is calculated from local upslope area drainage and slope angle and is often used to quantify topographic control on hydrological processes and to

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predict soil organic matter distribution (Sørensen et al., 2006; Pei et al., 2010). Thus the strong correlation between TWI and SOC 0-100 cm (R^2 = 0.63) indicate that the majority of SOC 0-100 cm variability is explained by hydrological conditions related to catenary position on slope. Ground ice in permafrost, which was included in our moisture content calculation, could be the reason for lower correlation between site measured soil moisture and SOC 0-100 cm than expected because of strong correlation between TWI and SOC 0-100.

Hydrological conditions control also the water content in the active layer, which is perquisite for increased pore-water pressures that cause mass wasting (Matsuoka, 2001; Harris et al., 2008; Lewkowicz and Harris, 2005). Slope angle affects not only soil drainage, but also the intensity of mass wasting (Williams and Smith, 1991). For this reason, the part of SOC 0-100 cm variation that is explained by slope angle and soil moisture, can also be attributed to mass wasting. Comparison between geomorphic disturbance groups (accumulation, mass wasting, undisturbed) revealed that sites with observed mass wasting contained significantly lower amounts of SOC 0-100 cm (Fig. 7 and Table 4). These groups included sites showing evidence of active or past mass wasting with various possible movement depths. Lantuit et al. (2012) analysed the active layer in stabilised RTS areas and undisturbed areas and showed that mass wasting can alter soil moisture regime and consequently SOC storage.

The difference between geomorphic disturbance groups was well reflected also in down-core trends of SOC, TN and dry bulk density (Fig. 8). The majority of SOC and TN in undisturbed sites was stored in the upper 70 cm, while in lower parts, which are likely a ground ice-rich material, very small amounts of SOC and TN were found. Sites characterised by mass wasting showed very high dry bulk densities deeper in profile, indicating that the material had been

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compacted by mass wasting processes, which has also been observed by Lantuit et al. (2012) on RTS. Sites undergoing peat and riverine accumulation showed a more homogeneous down-core distribution of SOC and TN storage. In two of the mass wasting sites (PG2157 and PG2158) we found particularly low SOC storage in the upper profile. This might indicate that mass movements as solifluction and active layer detaching have decreased SOC storage in these sites. The slightly higher SOC storage deeper in the core could have been caused by compaction.

Mass wasting may decrease SOC storage by material displacement and exposure of lower layers to aeration and increased microbial activity (Pautler et al., 2010), causing organic matter decomposition and carbon degradation (Koven et al., 2011). Pizano et al. (2014) attributed ¼ of storage loss to aerobic decomposition in material displaced by RTS activity. Mass movements that result in material removal, cause permafrost thaw and formation of a new active layer. Leaching of particulate organic carbon also has the potential to decrease SOC storage. Woods et al. (2011) demonstrated that dissolved organic carbon delivered from watersheds with slope disturbances is more labile than dissolved organic carbon from undisturbed watersheds. Lamoureux and Lafrenière (2014) demonstrated that slope disturbances can activate older particulate organic carbon from formerly undisturbed watersheds. Repeated mass wasting can also hinder plant growth and thus decreases organic matter accumulation.

The insignificant correlation between terrain variables and TN 0-100 cm (Table 3) could be the consequence of low nitrogen concentrations and low sample size or could indicate that TN storage is less influenced by terrain than SOC storage. The higher loss of carbon in

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comparison to nitrogen during organic material decomposition results in decreasing soil C/N ratios with decomposition (Meyers, 1994; Kuhry and Vitt, 1996). C/N ratios for 0-100 cm (Table 6) show significantly lower C/N ratios in sites characterised by mass wasting. Down-core trends (Fig. 8) show that mass wasting sites have significantly lower SOC contents, while TN storage is comparable to other sites. This might indicate that mass wasting promotes decomposition and carbon loss, but has a reduced impact on nitrogen storage. Low C/N ratios that we observed on Herschel Island can be explained by the presence of marine algae in organic matter (Meyers, 1994), which originates from the moraine material. C/N ratios below 9 in Strongly and Moderately Disturbed Terrain can be due to abundance of this material exposed by mass wasting. Very low C/N ratios could also result from measured inorganic nitrogen that could have been present in the samples.

Most of the variance in SOC 0-100 cm storage in our study was explained by catenary slope position. Nevertheless, geomorphic disturbances such as mass wasting show an important effect on soil properties and decrease in SOC storage. The effect of mass wasting on SOC storage might increase in the future under a warming climate (Grosse et al., 2011) with increasing retrogressive thaw slumping (Lantz and Kokelj, 2008) and an increase in active layer detachment activity (Lewkowicz and Harris, 2005). Continuous and slow mass wasting such as solifluction and soil creep can cause a significant relocation of material across the landscape (Lewkowicz and Clarke, 1998). The effect of this slow, continuous geomorphic disturbance on SOC and TN storage needs to be studied in detail because it is one of the most widespread processes of soil movement in periglacial environments (French, 2013) and the area affected by such disturbances across the circumpolar Arctic is likely much larger than the limited area affected by active layer detachments and RTS (Grosse et al., 2011).

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5.2 Suitability of ecological classification for SOC upscaling

Upscaling SOC to units derived from multispectral satellite imagery is a commonly used procedure in Arctic landscapes. We found that slope angle is an important determinant of SOC for the diverse terrain of Herschel Island. Adding slope angle layer to spectral bands of satellite image significantly improved the accuracy of our supervised classification of ecological units, and ultimately of SOC estimations. Horwath Burnham and Sletten (2010) used NDVI classes for SOC upscaling in the High Arctic of Greenland. The lack of correlation between NDVI and SOC found in our study suggests that using NDVI would not increase the accuracy of our SOC estimation. Adding information about slope angle, soil moisture and catenary slope position could improve SOC storage estimates in areas with diverse terrain similar to that of Herschel Island.

Comparing our ground truth points agreement accuracy (75 %) with that of other studies (78 %: Hugelius et al., 2012 and 77 %: Zubrzycki et al., 2013) showed that our classification accuracy is in the same range as theirs. The accuracy of our classification was high in Spits and Beaches, Strongly Disturbed Terrain, and Wet Polygonal Terrain units. The units affected by disturbance were characterised by lower accuracy, which likely reflects the transitional nature of these classes observed in the field. These units often morph from one into another without a clearly established boundary.

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5.3 SOC and TN storage and stocks

Comparing storage in our ecological units with storage in landscape units in other similar circum-Arctic studies (Table 7) shows comparable or higher storage in bog peatlands, shrub tundra, and floodplain terraces. There are no units comparable to our moderately- and strongly-disturbed units in the existing literature estimating SOC and TN storage, suggesting that the effect of mass wasting on SOC and TN storage was not included in existing storage estimations.

The mean SOC 0-100 cm storage on Herschel Island is estimated to be 34.8 kg C m^{-2}. Hugelius et al. (2010) calculated 33.8 kg C m^{-2} for the Tulemalu Lake area (Central Canadian Arctic) and Hugelius et al. (2011) calculated 28.1 kg C m^{-2} for the Usa basin. Zubrzycki et al. (2013) calculated 25.7 kg C m^{-2} for the Holocene part of the Lena River Delta. The same authors reported TN 0-100 cm storage in the Holocene part of the Lena River Delta to be 1.1 kg N m^{-2}, which is three times lower than on Herschel Island (3.4 kg N m^{-2}). In general, SOC storage on Herschel Island is similar to values reported in comparable environments elsewhere. In the Northern Circumpolar Soil Carbon Database, Hugelius et al. (2013a) reported 55.3 kg C m^{-2} of SOC 0-100 cm storage for the whole of Herschel Island, which overestimated the SOC 0-100 cm storage by 59 %.

The highest SOC and TN storage in the uppermost metre occurs in the Wet Polygonal Terrain unit. This is largely because peat has probably been accumulating in the thermokarst depressions and flat valley bottoms since the beginning of the Holocene (Fritz et al., 2012). In these parts of the landscape, wet anoxic conditions favour the preservation of organic carbon and nitrogen (Hobbie et al. 2000). The second largest SOC and TN storage was observed in

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slightly or undisturbed ecological units with mineral soil that has undergone cryoturbation or has been influenced by fluvial accumulations (Smith et al, 1989).

6 Conclusions

We found that terrain has an important influence on SOC storage on Herschel Island. The majority of SOC storage variance (63 %) was explained by the site catenary position on slope, which governs the differences in soil moisture regimes. We also inferred that sites characterised by different geomorphic disturbances result in different SOC storage. Mass wasting sites showed material compaction and decreased SOC storage particularly in the upper profile. Increased mass wasting could lead to enhanced mobilization of carbon and nitrogen stocks, which could have important impacts on both the terrestrial and marine components of this Arctic coastal ecosystem. While studies dealing with decreased SOC and TN in permafrost environments due to mass wasting that occur as single rapid event (e.g. RTS) exist, the importance of slow, continuous mass wasting as solifluction has not yet been taken into account. We estimated average SOC 0-100 cm and TN 0-100 cm on Herschel Island to be 34.8 kg C m^{-2} and 3.4 kg N m^{-2}. High-resolution studies such as ours will help to improve circum-Arctic storage estimates and projections of future fluxes of carbon and nitrogen with warming.

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Table 1. Basic properties of ecological units according to the field survey and Smith et al. (1989).

Ecological unit	Name defined by Smith et al. (1989)	Topography	Geomorphic disturbance	Slope (°)	Dominant soil type	Typical vegetation
Spits and Beaches	Avadlek	beaches, spits, and other coastal accumulation forms	interchanging coastal sediment accumulation and erosion	1 (0-1)	Regosolic Static Cryosol	*Leymus mollis, Saxifraga,* and *Petasites*
Wet Polygonal Terrain	Guillemot	Level and depressional ice-wedge polygonal terrain	frost cracking and peat accumulation	2 (0-3)	Gleysolic Turbic Cryosol	*Eriophorum* and Bryophytes in drier areas (polygon rims) and *Carex* and Bryophytes in wettest areas.
Hummocky Tussock Tundra	Herschel	flat to gently sloping uplands with distinctive hummocks	absent	1 (0-4)	Orthic Turbic Cryosol	*Eriophorum* tussock tundra
Slightly Disturbed Uplands	Komakuk	gently sloping uplands to gentle slopes	slow downslope movements and gelifluction	4 (0-6)	Orthic Turbic Cryosol	*Salix arctica, Dryas integrifolia* and Fabaceae
Alluvial Fans	Orca	alluvial fans and other riverine sediment accumulations	fluvial accumulation	2 (1-6)	Regosolic Static Cryosol	*Salix richardsonii* shrub vegetation
Moderately Disturbed Terrain	Plover and Jaeger	complex slopes with unvegetated patches	moderate downslope movements, gullying and active layer detachments	5 (2-18)	Regosolic Static Cryosol	*Salix, Dryas,* Fabaceae, *Saxifraga, Petasites,* and a range of other taxa
Strongly Disturbed Terrain	Thrasher	steep slopes, cliffs, and retrogressive thaw slumps	strong gullying, active coastal erosion, slumping and other mass wasting	15 (8-26)	Regosolic Static Cryosol	Sparsely vegetated with *Salix arctica, Lupinus, Myosotis, Senecio*

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Table 2. Main site and core properties for cores retrieved on Herschel Island. The core locations are indicated in Fig. 1. Ecological unit names in brackets were defined by Smith et al. (1989). The paleo-active layer depth was deducted from cryostructures below thaw depth.

Core-Nr.	Ecological unit name	Latitude (°)	Longitude (°)	Elevation (m)	Slope angle (°)	Slope exposition (°)	Total sampling depth (cm)	Observed thaw depth (cm)	Paleo-active layer depth (cm)	NDVI	SOC storage 1 m (kg m^{-2})	TN storage 1 m (kg m^{-2})	No. of samples
J01	Spits and Beaches (Avadlek)	69.56841	-138.91560	1	0	-1	40	40	> 40	0.33	5.5	0.2	8
PG2150	Wet Polygonal Terrain (Guillemot)	69.57957	-138.95726	26	0	-1	218	15	27	0.62	91.0	1.5	12
PG2151	Wet Polygonal Terrain (Guillemot)	69.57952	-138.95734	23	0	-1	250	31	63	0.60	78.9	1.0	13
PG2152	Hummocky Tussock Tundra (Herschel)	69.57148	-139.02565	57	2	70	63	34	49	0.60	45.0	0.9	5
PG2154	Hummocky Tussock Tundra (Herschel)	69.57184	-139.02545	57	2	70	198	18	19	0.67	33.9	0.5	12
PG2155	Slightly Disturbed Uplands (Komakuk)	69.57467	-139.00703	32	1	135	197	31	52	0.57	36.5	1.0	13
PG2156	Alluvial Fans (Orca)	69.57082	-138.89462	5	1	12	227	49	60	0.63	39.5	0.9	13
PG2157	Moderately Disturbed Terrain (Plover+Jaeger)	69.57179	-138.89030	15	7	158	190	46	67	0.68	28.3	0.6	12
PG2158	Strongly Disturbed Terrain (Thrasher)	69.57600	-138.89360	50	9	154	143	77	98	0.35	56.6	1.5	8
PG2159	Alluvial Fans (Orca)	69.57340	-138.99677	2	5	277	200	28	43	0.74	16.3	1.0	12
PG2162	Moderately Disturbed Terrain (Plover+Jaeger)	69.57426	-138.99422	40	8	270	70	70	> 70	0.59	11.9	0.2	6
PG2163	Hummocky Tussock Tundra (Herschel)	69.57871	-138.87083	93	4	203	230	33	46	0.69	20.9	0.6	14

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Table 3. Correlations between SOC and TN site storage and variables. Person's r and R-squared values were calculated for numerical variables. Statistical significance is shown by the p-value, which was corrected for multiple comparisons with False discovery rate correction.

		Slope	Topographical wetness index	Moisture	NDVI	Elevation
SOC 0-100 cm	R	-0.68	0.79	0.69	0.23	-0.14
	R-squared	0.46	0.63	0.47	0.05	0.02
	p-value	**0.023**	**0.004**	**0.020**	0.504	0.690
	p-corrected	**0.038**	**0.018**	**0.038**	0.630	0.690
TN 0-100 cm	R	-0.42	0.51	0.10	-0.08	0.10
	R-squared	0.18	0.26	0.01	0.01	0.01
	p-value	0.195	0.109	0.779	0.807	0.776
	p-corrected	0.488	0.488	0.807	0.807	0.807

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Table 4. P-values from Student's t-test group means comparison.

	SOC 0-100 cm	TN 0-100 cm
Mass wasting – Undisturbed	0.002	0.23
Mass wasting – Accumulation	0.04	0.14
Accumulation – Undisturbed	0.17	0.87

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Table 5: Contingency table of the classification accuracy between observed (ground truth points) and predicted (classification) ecological units.

Predicted\Observed	Spits and Beaches	Wet Polygonal Terrain	Hummocky Tussock Tundra	Slightly Disturbed Uplands	Alluvial Fans	Moderately Disturbed Terrain	Strongly Disturbed Terrain	Total	User's accuracy (%)
Spits and Beaches	3	0	0	0	0	0	0	3	100.0
Wet Polygonal Terrain	0	3	0	0	0	0	0	3	100.0
Hummocky Tussock Tundra	0	0	7	3	0	0	0	10	70.0
Slightly Disturbed Uplands	0	0	1	2	0	0	0	3	66.7
Alluvial Fans	0	0	0	0	4	0	0	4	100.0
Moderately Disturbed Terrain	0	0	0	2	1	7	0	10	70.0
Strongly Disturbed Terrain	0	0	0	2	0	1	4	7	57.1
Producer's accuracy (%)	100.0	100.0	87.5	22.2	80.0	87.5	100.0		

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707 Table 6. SOC, TN storage and C/N ratios for different depth ranges on Herschel Island.

Ecologicl unit	Area (km^2)	SOC storage 0-30 cm (kg m^{-2})	SOC storage 0-100 cm (kg m^{-2})	SOC storage 0-200 cm (kg m^{-2})	TN storage 0-30 cm (kg m^{-2})	TN storage 0-100 cm (kg m^{-2})	TN storage 0-200 cm (kg m^{-2})	C/N ratio 0-30 cm	C/N ratio 0-100 cm	C/N ratio 0-200 cm
Spits and Beaches	1.1	5.5	5.5	5.5	0.2	0.2	0.2	24.6	24.6	24.6
Wet Polygonal Terrain	8.6	22.8	84.9	132.1	1.3	4.6	7.8	18.2	18.6	16.8
Hummocky Tussock Tundra	28.2	11.9	38.4	49.6	0.8	4.0	6.9	14.4	9.6	7.1
Slightly Disturbed Uplands	35.0	10.6	39.5	46.5	0.9	3.4	4.5	12.1	11.5	10.4
Alluvial Fans	1.3	15.5	42.5	66.0	1.1	3.4	5.9	14.2	12.3	11.2
Moderately Disturbed Terrain	24.1	5.8	14.1	22.7	0.6	2.0	3.3	9.9	7.0	6.9
Strongly Disturbed Terrain	12.6	3.0	20.9	44.3	0.6	3.7	7.6	5.2	5.6	5.9
Herschel Island	110.9	10.0	34.8	48.3	0.8	3.4	5.4	12.6	10.4	8.9

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Table 7. Comparing SOC 0-100 cm storage in our ecological units to storage in comparable units from other studies.

Herschel Island		Comparable studies			
Ecological unit	SOC 0-100 cm sorage (kg m^{-2})	Comparable unit in other studies	Study Area	SOC 0-100 cm sorage (kg m^{-2})	Reference
Wet Polygonal Terrain	85	bog peatlands	Central Canadian Arctic	80	Hugelius et al. (2010)
			Alaska	94-82	Michaelson et al. (1996)
Hummocky Tussock Tundra and Slightly Disturbed Uplands	40	shrub tundra	Western Siberia	10-40	Hugelius et al. (2011)
			Central Canadian Arctic	21-40	Hugelius et al. (2010)
Alluvial Fans	42	holocene floodplain terrace	Lena River Delta	30	Zubrzycki et al. (2013)

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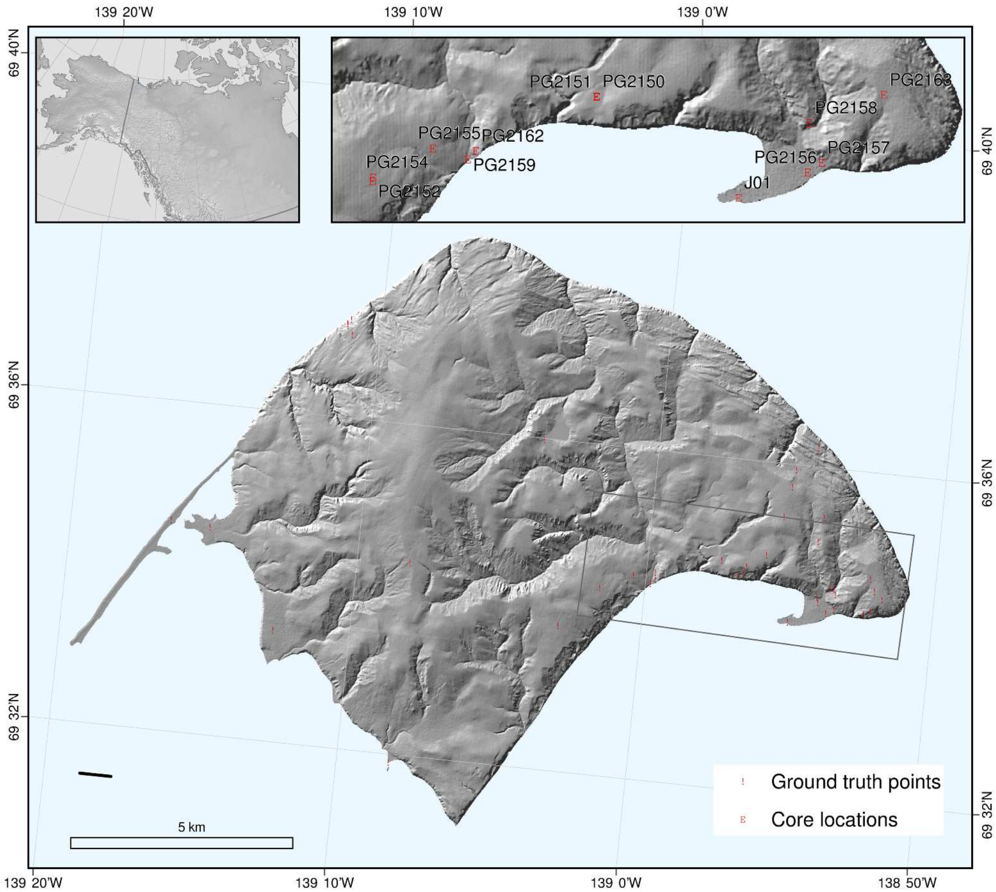

Figure 1. Overview map of Herschel Island with ground truth points used for supervised classification. The upper left panel shows the location of Herschel Island. The upper right panel, whose area is delineated by the rectangle in the lower main figure, shows the coring locations on Herschel Island.
275x247mm (300 x 300 DPI)

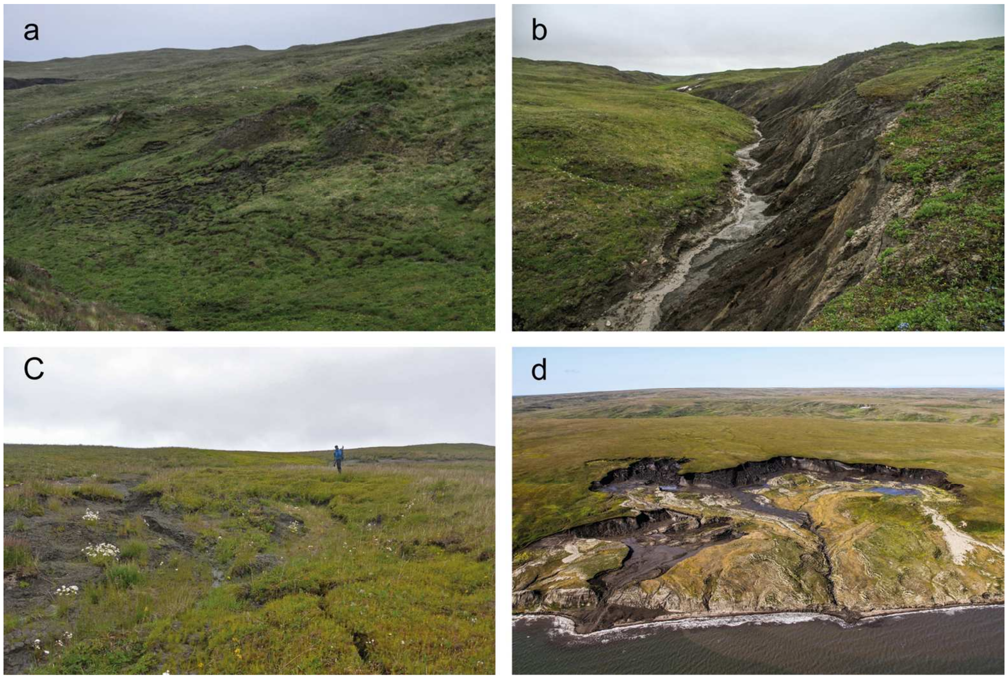

Figure 2. Examples of mass wasting on Herschel Island: (a) solifluction, (b) gullying, (c) active layer detachment, and (d) retrogressive thaw slumping.
140x94mm (300 x 300 DPI)

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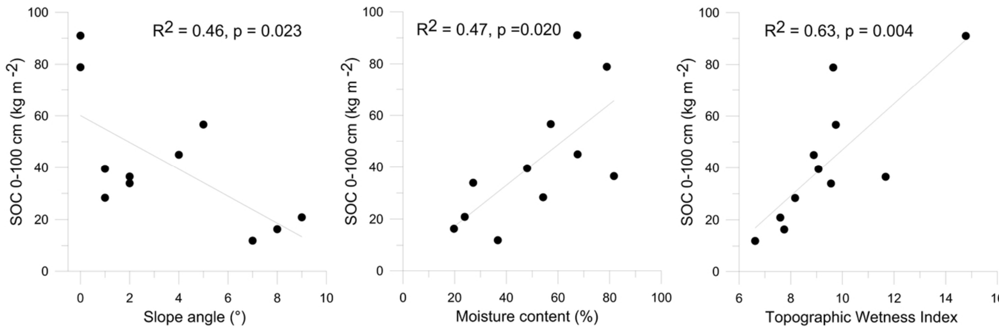

Figure 3. SOC 0-100 cm values plotted against slope angle, moisture content and Topographic wetness index with added linear trend line.
125x40mm (300 x 300 DPI)

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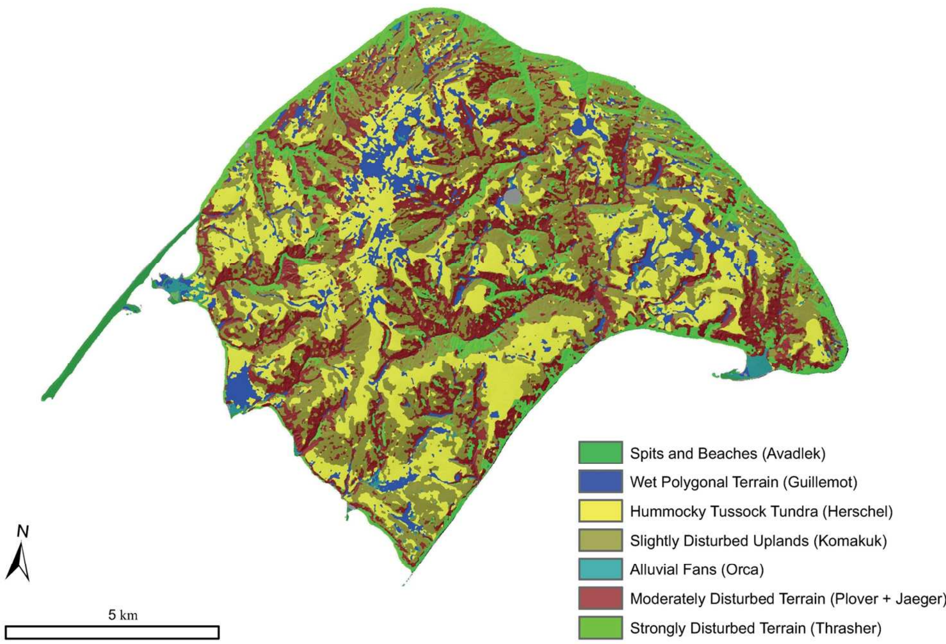

Figure 4. Ecological units on Herschel Island. The map is post-processed output of supervised classification. These units were used for upscaling SOC and TN.
146x102mm (300 x 300 DPI)

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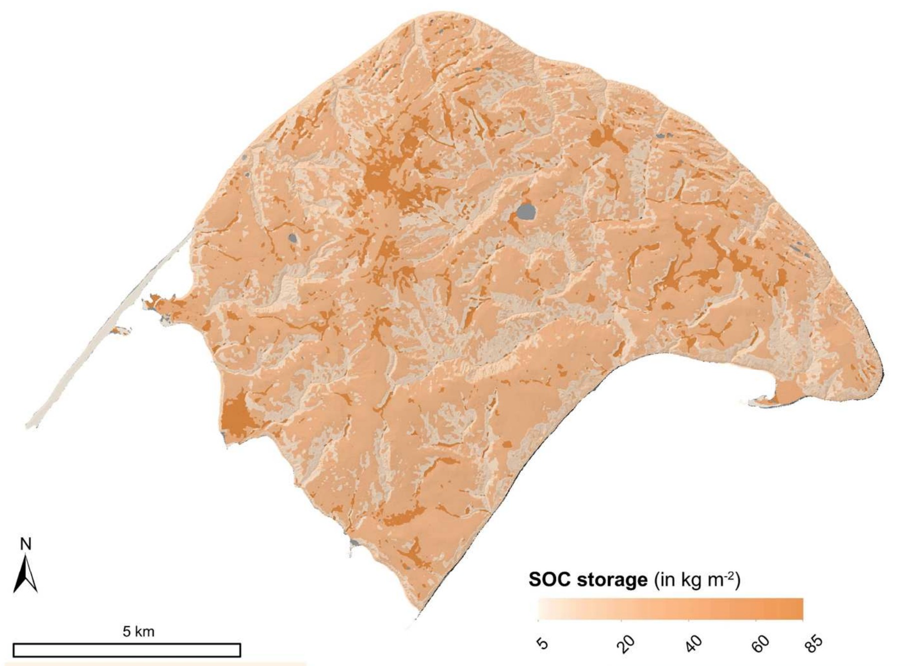

Figure 5. Map of SOC storage on Herschel Island for the uppermost metre of the soil. This map is the result of upscaling SOC 0-100 cm values to ecological units in Fig. 3.
147x104mm (300 x 300 DPI)

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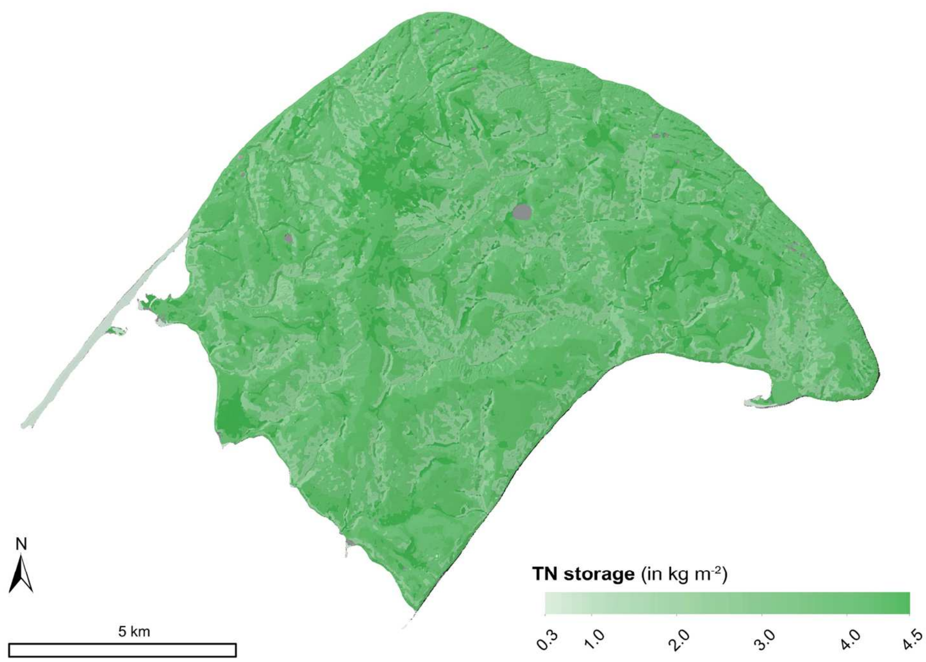

Figure 6. Map of TN storage on Herschel Island for the uppermost metre of soil. This map is the result of upscaling TN 0-100 cm values to ecological units in Fig. 3.
147x104mm (300 x 300 DPI)

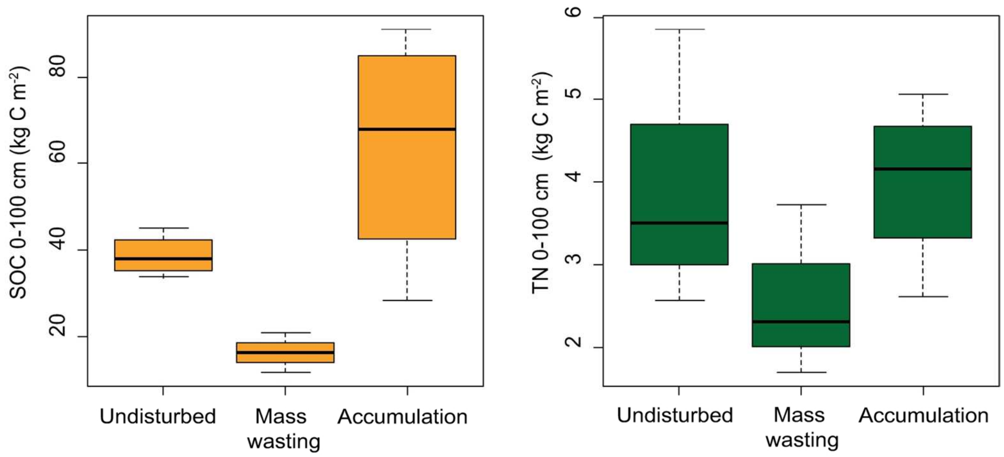

Figure 7. Boxplots of core SOC 0-100 cm and TN 0-100 cm storage grouped by geomorphic disturbance. Grouping of sites is described in section 3.5.
140x76mm (300 x 300 DPI)

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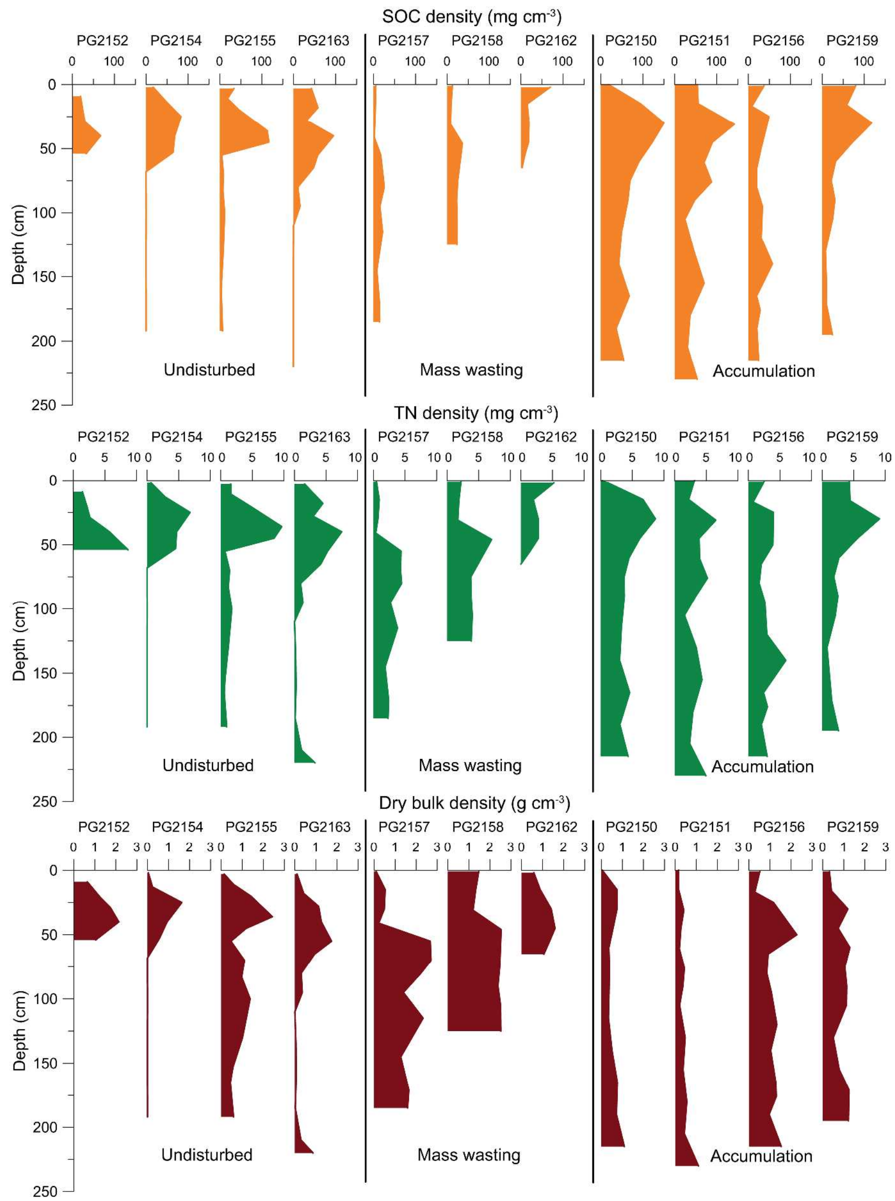

Figure 8. Down-core trends for SOC density, TN density and dry bulk density. Cores are grouped according to geomorphic disturbance. Cores PG2154 and PG2163 included an ice wedge ice which is indicated by their low dry bulk density in deeper soil horizons.
419x570mm (600 x 600 DPI)