University of Hohenheim

Institute of Soil Science and Land Evaluation

Mapping of soil organic carbon and nitrogen in two small adjacent Arctic watersheds on Herschel Island, Yukon Territory

Master-Thesis (30 ECTS)
Agricultural Sciences- Major Soil Sciences

Isabell Eischeid (588881)

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First examiner: Prof. Dr. Thilo Streck
Second examiner: Prof. Dr. Hugues Lantuit

ALFRED-WEGENER-INSTITUT
HELMHOLTZ-ZENTRUM FÜR POLAR-
UND MEERESFORSCHUNG

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List of Abbreviations

ALD	Active layer detachment
ANOVA	Analysis of variance
CN	Organic carbon to nitrogen ratio
DEM	Digital elevation model
HE	Herschel
HK	Herschel-Komakuk
IC	Ice Creek
ICE	Ice Creek East
ICW	Ice Creek West
KO	Komakuk
NDVI	Normalized difference vegetation index
NMDS	Non-metric multidimensional scaling
PCA	Principal component analysis
PJ	Plover-Jaeger
RTS	Retrogressive thaw slump
SOC	Soil organic carbon
SZ	Shrub Zone
TH	Thrasher
TN	Total nitrogen
TOC	Total organic carbon
TWI	Topographic wetness index
WT	Wet Terrain

Abstract

Permafrost soils are particularly vulnerable to global climate change, and warming air temperatures could turn them from carbon sinks into carbon sources. Estimates of Arctic carbon stocks are still highly uncertain, despite their importance to predict the magnitude of CO_2 and CH_4 release to the atmosphere, a process termed the Permafrost Carbon Feedback. Because most of the Arctic is difficult to access and survey, remote sensing techniques bear the capacity to fill spatial gaps and map the changing landscape at wider scales. Recent studies have attempted to use multispectral images, such as Landsat, to estimate soil total organic carbon (TOC) and total nitrogen (TN) storage. Yet, most studies worked on a regional to global scale and used relatively coarse landscape classes. Since TOC and TN storage is known to be highly spatially variable in the landscape, high resolution estimates of TOC and TN storage are necessary to estimate the potential impact of thawing permafrost (and the subsequent release of CO_2 and CH_4) to the atmosphere. This project is one of the first to use high resolution images (1.65m GeoEye (4 spectral bands: blue-infrared), 2m DEM) to predict SOC and TN storage within different Tundra vegetation classes in a small (3 km^2) twin watershed (Ice Creek) on Herschel Island, Yukon, Canada. Vegetation classes were based on indicator species and geomorphic disturbance levels. Remote sensing detection accuracy varied strongly between classes. Field based moisture measurements were most strongly correlated with the carbon to nitrogen (CN) ratio, TOC and TN (ρ =0.84, ρ =0.74 ρ =0.65, $p<0.05$). However, slope and the normalized difference vegetation index (NDVI) also had a statistically significant relationship to CN and TOC. This suggests that fine scale estimates of carbon and nitrogen stocks are possible using few spectral bands from high resolution images. The active layer of Ice Creek watershed contains 33391 tonnes of TOC and 3635 tonnes of TN, which is lower than the average value reported for Herschel Island by the Northern Circumpolar Soil Carbon Database. Carbon and nitrogen are not evenly distributed within the watershed. Flat upland terrain and tall erect bush areas contained the largest amount TOC and TN. Lowest contents could be found in the steep and frequently eroded zones. High carbon accumulation along the stream banks suggests that fluvial processes do not remove all the eroded sediments from the watershed. An intensification of summer rainfall and warmer temperatures could alter the hydrological patterns of the watershed and current accumulation sites may release more carbon from the catchments to the Beaufort Sea. High correlation between soil moisture and TOC and TN contents found in this thesis shows that moisture information retrieved from satellite radar data could provide additional information on soil properties. This thesis also shows that detailed studies on remobilization of carbon in the catchments and atmospheric losses of carbon are crucial to understand the role small watersheds play in the face of a changing climate.

1. Introduction

The detected and projected climate change is particularly severe in the Arctic region because changes in cloud cover and sea ice significantly alter the thermal balance of this area (Holland & Bitz, 2003). Temperatures are expected to increase and precipitation patterns may change more rapidly than in other parts of the world (IPCC, 2007). Precipitation patterns in cold environments are particularly important for landscape dynamics and nutrient turnover in the soil. Higher snowfall insulates the soil in the winter and promotes higher rates or mineralization, whereas at the same time late snow melt shortens the growing season by up to a month and alters vegetation distribution (Jones et al., 2011; Cooper, 2014). Intensive rainfall in late summer, where the active layer of the permafrost is deepest can result in mass wasting and erosion events (Lamoureux et al., 2014).

In most cold environments, organic matter accumulation is high because low temperatures prevent high nutrient turnover rates (Hobbie et al., 2000). Furthermore, cryoturbation buries organic matter rich topsoils and locks them from mineralization (Bockheim, 2015). Therefore arctic soils have high organic carbon contents that have been part of long term storage (Hobbie et al., 2000, Hugelius et al., 2014). High carbon storage means that thawing of permafrost could potentially have large impact on the Earth’s climate, turning them from carbon sinks into carbon sources (Schuur, 2015). Permafrost thaw is part of a self-accelerating process where thawing releases more greenhouse gases which in turn enhance the climate change and is therefore difficult to slow down (Schuur, 2015). This process is termed the Permafrost Carbon Feedback (Schaefer et al, 2014). Several major research projects aim to estimate global arctic carbon stocks but estimates are still highly uncertain, despite their importance to predict the magnitude of CO_2 and CH_4 release to the atmosphere (Hugelius et al., 2014). Additionally, the role and quantity of nitrogen in these soils has been largely unstudied. Nitrogen plays a major role in carbon mineralization, but its presence can lead to the release of the greenhouse gas nitrous oxide (NO_2) To date, only very few studies have tried to estimate nitrogen stocks in the arctic (Obu et al., 2015).

Loose sediments moved during the last glaciation are held together in the frozen state by permafrost. Thawing permafrost is therefore particularly susceptible to erosion (Lamoureux & Lafrenière, 2014). Every year, during the few months where temperatures are above zero, the arctic landscape becomes very dynamic. Coastal areas are undergoing erosion and slumping, the active layer of the permafrost may detach in mass wasting events and thermal erosion channels may move large amounts of sediments and organic matter within the landscape or into the sea (Pautler et al., 2010; Lantuit et al., 2012; Harms et al., 2014). The contribution from most of these processes to the coastal zone in terms of sediment, organic carbon and nutrients has been studied by many authors (Lantuit & Pollard, 2008; Lantuit et al., 2012; Sánchez-García et al., 2014; Macdonald et al., 2015). However, sediment fluxes and carbon release from small watersheds is not well known, although these are numerous along the Arctic coast (Beylich & Warburton, 2007; Lamoureux & Lafrenière, 2014).

Small watersheds are considered small when the catchment area is 30 km^2 or less (Beylich & Warburton, 2007). Small coastal watersheds are a common landform across large parts of the Arctic (Lamoureux & Lafrenière, 2014). Better estimates about their cumulative impact on sediment release are necessary to understand their impact on downstream aquatic systems and ultimately on the Earth's climate (Harms et al., 2014; Lamoureux & Lafrenière, 2014). A few of these watersheds have been instrumented to monitor discharge and sediment release, for example in Kärkevagge in Sweden and at Cape Bounty in Canada (Bartsch et al., 2009; Lamoureux & Lafrenière, 2014). The Ice Creek catchment, located on Herschel Island, in the western Canadian Arctic, is a typical small coastal watershed and will be instrumented in the near future to monitor its reaction to a changing climate.

Before undertaking any monitoring efforts, reliable baseline data on terrain and carbon storage is necessary, in order to assess how much sediment and organic matter may move within or out of the system. These data can be retrieved in the field, by collecting soil samples and analyzing them in the laboratory, and with the help of remote sensing imagery to extrapolate sample data to wider areas. Remote sensing has become an important tool in arctic research due to the inaccessibility of most regions. The Arctic is regularly monitored by low resolution satellites that provide information about biomass and productivity (Raynolds et al., 2006). However, medium and high resolution images are not obtained as regularly because of scarcer revisit times, long periods of darkness and often prevailing cloud cover in summer (Stow et al., 1993). Remote sensing studies that estimate regional arctic carbon stocks mostly utilized medium resolution images (30 meter). These images usually capture a wide range of wavelengths from which information on land cover, biomass and wetness can be derived (Fraser et al., 2012, Hugelius et al., 2014, Fuchs et al., 2015). A 30 m resolution is nonetheless not able to accurately capture the terrain variability (and hence organic matter storage) of small watersheds (Beylich & Warburton, 2007).

This study will test the suitability of combining two meter resolution GeoEye images with field surveys to accurately predict soil organic carbon and nitrogen storage in the Ice Creek watershed on Herschel Island, western Canadian Arctic. The high resolution outputs of this thesis will be compared with other datasets, such as the Northern Circumpolar Soil Carbon Database (Hugelius et al., 2013) to inform future upscaling strategies. It will also provide baseline data for future hydrological studies within the Ice Creek watershed on Herschel Island.

There were two major objectives of this study:

1) To test the suitability of using ecological classes (which include a qualitative assessment of vegetation, slope and disturbances) and simple vegetation classes to predict soil organic carbon (TOC) and nitrogen (TN) within the Ice Creek watershed on Herschel Island.

   Suitable is defined as:
   a) Detectable through remote sensing methods with GeoEye images
   b) Characterised by low variation within and low redundancy of TOC and TN contents between classes

2) To analyze and discuss the spatial distribution of soil organic carbon and nitrogen within the active layer of Ice Creek watershed. And more specifically:
   a. Evaluate how terrain characteristics affect TOC and TN storage
   b. Use ecological classes to understand how biotic and abiotic factors influence TOC and TN accumulation
   c. Use cross sections through the watershed to identify TOC mobilization and accumulation sites

2. Background

2.1 Cryosols

Definition

The word Cryosol comes from the Greek words for icy - cold and soil. The concept that frozen soils need their own study and classification system was introduced to the English speaking world by the Russian researcher Nikiforoff in 1928 (in Bockheim, 2015). For a couple of decades, there has been hesitation about classifying frozen soils as real soils because biological and chemical activity is limited in the frozen state (Bockheim, 2015). However, since 2006, it has been accepted as a key soil group in the World Reference Base for Soils (WRB). It is defined as "soils having one or more cryic horizons within 100 cm from the soil surface". Whereas cryic is: "a perennially frozen soil horizon in mineral or organic materials".

A cryic horizon has:

1. continuously for ≥ 2 consecutive years one of the following:
    a. massive ice, cementation by ice or readily visible ice crystals; or
    b. a soil temperature of ≤ 0°C and insufficient water to form readily visible ice crystals; and
2. a thickness of ≥ 5 cm

(IUSS Working Group, 2014)

The Canadian System of Soil Classification (CSSC, 1988) has a separate order for Cryosols and defines them as follows: "Cryosolic soils are formed in either mineral or organic materials that have permafrost either within 1 m of the surface or within 2 m if the pedon has been strongly cryoturbated laterally within the active layer, as indicated by disrupted, mixed, or broken horizons. They have a mean annual temperature ≤0°C. Differentiation of Cryosolic soils from soils of other orders involves either determining or estimating the depth to permafrost." The Canadian system then further divides the Cryosolic order into three great groups: Turbic Cryosols, Static Cryosols and Organic Cryosols. Table 1 describes the defining characteristics of these great groups (CSSC, 1988)

Table 1: Cryosolic orders

Cryosolic Order

	Turbic Cryosol	Static Cryosol	Organic Cryosol
Soil	mineral	mineral	organic
Cryoturbation	marked, usually patterned ground	none	none
Permafrost	within 2 m of surface	within 1 m of surface	within 1m of surface

Not all classification or taxonomical systems include Cryosols (or Gelisols in the USA) because national systems usually only focus on soils occurring within their national boundaries. For the purpose of this report, the Canadian System of Soil Classification (CSSC, 1988) will be used to describe soils with cryosolic properties.

Three part model

Independently of the classification system, Cryosols are usually divided into three distinct layers: The active layer, transient layer and permafrost. The following section, unless indicated differently, describes the 3 part system defined by Bockheim (2015).

Active Layer

The active layer is the upper section of the soil which thaws in summer and refreezes in winter. Its thickness depends on snow cover, vegetation, soil moisture and soil thermal properties. In the high Arctic, active layer depth is often very shallow (0.1-0.15m), whereas in alpine regions it can be deeper than eight meters (Bockheim, 2015). The dominating soil process in the active layer is cryoturbation. Freeze-thaw cycles cause soil sediments to get sorted by size. This changes the physical properties of the soil and, similar to bioturbation, soil organic carbon (SOC) gets accumulated within the active layer. The structure of the soil is often dependent on the degree of cryoturbation and can be granular to blocky. Massive structures often form when the soil desiccates between the upper and lower freezing front in late Fall (cryodessication). The unfrozen active layer can easily detach from the frozen ground below and gelifluction processes may occur. The speed of the soil movement depends on the slope and the ice content of the permafrost. If the slope is steep and enough ice is present, sudden active layer detachments can take place, leaving a distinct brim, bare ground and mobilizing large amounts of SOC at once (Pautler et al., 2010).

Transient Layer

Researchers are starting to recognize the transient layer as a distinct feature, it is a concept suggested by Russian scientists to define the zone within the soil that only infrequently melts during the summer (Bockheim, 2015). It is therefore the zone between the active layer and the permafrost underneath. The end of the transient layer defines the boundary of the maximum long term thaw depth of the permafrost. The physical properties of the transient layer are similar to the active layer and permafrost but due to its location it encompasses distinct cryogenic structures and often signs of old cryoturbation (Shur et al., 2005). This makes the transient layer particularly important for climate change related studies because its structure gives insights to periodic and long term warming and cooling periods.

Permafrost

Permafrost is the zone that stays permanently frozen throughout the year. Permafrost can consist of soil, bed rock, ice or a mixture thereof. The permafrost depth can vary between one meter and 1500 meters. High ice content leads to the occurrence of excess ice and a water saturation of over 100 percent. When the excess ice thaws, the soil loses its volume and stability.. One method of defining permafrost is by the percentage area covered, continuous (90-100%), discontinuous (50-90%), sporadic (10-50%) and isolated patches (0-10%). The deep permafrost is usually very old (10 000 years and more) and acts as a natural history archive. The near-surface permafrost can be used to assess the source and age of organic matter as well as soil water.

Distribution of Cryosols

Depending on the definition and assessment method, the estimated area covered by Cryosols globally ranges from 11.3 to 25 million km^2 (Bockheim, 2015). The most recent study estimates claim that there are 22±3 million km^2 of Cryosols, which is about 25% of the Earth's land surface (Gruber, 2012). Russia and Canada have the largest Cryosol covered areas, followed by Alaska, China and Greenland. Cryosols occur in the circum-arctic (83%), in high mountain regions (17%) and to a very small extent in Antartica (0.1%). Most of the circum-arctic Cryosols are mineral and roughly 9% are organic.

Figure 1: Circum-arctic permafrost distribution (Brown et al., 1998).

2.2 Watershed disturbances

The character of landscapes in cold environments, and hence of small catchments, is often shaped by a high degree of disturbance. These disturbances can be of varying dimensions and origins and will be described below.

Cold environment disturbances

Some disturbances are unique to cold environments where the phase change of water from solid to liquid (and vice versa) creates a highly dynamic landscape, the mechanisms of which, however are still poorly understood (Warburton, 2007).

Permafrost can get degraded by external disturbances. These include disturbances that are of anthropogenic or natural origin. Mining activities, for example, open up large areas in the landscape, removing vegetation and interfering with natural processes. Because degradation rates in cold environments are slower than in temperate and tropical climates, anthropogenic pollution can persist for much longer time spans (Thomas et al., 1992). Fires in permafrost regions can also release large amounts of carbon within a short time frame and are expected to increase in magnitude and frequency with climate change (Harden et al., 2010).

Seasonal freeze thaw events alter the soil structure and are a vital part of what defines Cryosols (Bockheim, 2015). A warming Earth changes the dynamics of seasonal freeze-thaw cycles and therefore the frequency and magnitude of Cryosol specific disturbances (Schuur et al., 2015). Some of the most important disturbances will be described below. These disturbances are often linked with each other which makes it difficult to single out separate processes without complex field and laboratory analyses (Beylich & Warburton, 2007).

Cryoturbation is slope independent and is comparable to bioturbation but an albeit slower process. Instead of tunnels being dug by animals that bring down organic matter, cryoturbation slowly turns the soil by frost heaving and through freeze thaw cycles and therefore burying some parts of the upper organic horizon in deeper layers of the soil (Bockheim, 2015). Carbon accumulation is consequently locally induced and not the result of relocation from other areas within the landscape. Recent cryoturbation can be identified through open ground scars within the vegetation cover (Bockheim, 2015). Ancient cryoturbation can be detected by the presence of organic matter pockets close to the permafrost table and below. The age of these organic deposits can be determined through radiocarbon dating (Hugelius et al., 2010). Frost heave and cryoturbation can further trigger the emergence of frostboils, circular areas where sediments are pushed upward preventing plants from growing there (French, 2007).

Gelifluction is similar to solifluction which is the downward movement of soil destabilized through seasonal frost, only that gelifluction is defined as the slow downward movement of unfrozen material on a frozen surface. The occurrence of gelifluction is influenced by the ice structures in the permafrost and the steepness of the slope. (Bockheim, 2015) The speed of gelifluction is around 1-3 cm/year (Bockheim, Bartsch et al., 2009). Related to gelifluction is the formation of thermal erosion channels. They form when warm temperatures cause meltwater to flow downslope and contribute to thaw the underlying permafrost. Erosion and loss of ice volume lead to a deepening of water channels and expose them to solar radiation (Harms et al., 2014). Thermal erosion channels can, but not necessarily, form within one season and usually persist for a long time because snow accumulations in the winter protect them from cold temperatures (Jorgenson & Osterkamp, 2005).

Cryodessication occurs when the freezing front on the permafrost table drains the remaining water from the active layer. This leads to a soil texture change and can produce platy layers, blocky structures or structureless soil. On the surface it can often be recognized through deep cracks that extent toward the permafrost. In saline soils, cryodessication may create a salt coating on the surface (Bockheim, 2015).

Active Layer detachments (ALD) get triggered when an oversaturation of the active layer creates an overburden in the soil. Oversaturation can be caused by ground ice melt, upslope drainage or heavy rainfall (Hodgson, 1977; French, 2007, Lamoureux & Lafrenière, 2009). The sliding material can reach speeds of up to 9 m/h (Lewkowicz, 2007). The character of the ALD greatly depends on the original substrate, magnitude, vegetation and slope characteristics (Lewkowicz, 2007). Other than displacing soil downslope, ALDs also can, but not necessarily, bury topsoil by forming fractures and folds during movement (Lewkowicz, 2007). ALDs occur only periodically but because of their magnitude they have the potential to significantly alter sediment budgets and fluvial processes in the landscape (Lamoureux & Lafrenière, 2009).

Retrogressive Thaw slumps (RTS) are semi-circle shaped incisions that form during mass wasting events in areas where large amounts of ground ice get exposed to air and solar radiation (Lantuit et al., 2012). Melting of the ground ice causes the sediments to collapse, collect on the slump floor and drain out of the area (Lantuit et al., 2012). They are typical for coastal areas where they are initiated by wave erosion but can also occur inland. Fluvial erosion or other slope processes like active layer detachments could expose enough ice to cause the collapses (French, 2007). Headwall retreat can be up 8 meters per year and is the most erosive process in periglacial environments today (French, 2007). RTSs stabilize when the end of an ice wedge is reached or collapsed debris protects the ice wall from further thawing. They can get reactivated with time (French, 2007).

Temperature independent slope processes

Despite the prominence of cold environments specific disturbances, it is essential to recognize that slope and disturbance processes common for warmer areas also occur in cold landscapes. Yet, the magnitude of weathering, aeolian, fluvial and slope process regimes all get altered through underlying cryo-processes (Beylich & Warburton, 2007). Cryo-disturbances often destabilize the soil and create open ground surfaces. These are then highly susceptible to erosion. For example, the formation of thermal erosion channels gets triggered by thawing but common erosional processes carry sediments further downstream (Harms et al., 2014). This thesis does not distinguish between cryo-disturbances and other common slope processes because of their interrelated nature and the often very similar surficial expression in the landscape. However, it does refer to temporal framework of common disturbances, since carbon sequestration in undisturbed areas generally takes a much greater time than the immediate burial of organic matter in active layer detachments for instance (Bartsch et al., 2009).

2.3 Ecological and vegetation classes of Herschel Island

The ecological and vegetation classes on Herschel Island are unique to the area and readers of this study will require some information about each of the classes to fully understand it. The ecological classes of Herschel Island were defined by Smith et al. (1989) as holistic map units that encompass information about vegetation, soil type and landscape processes. The names chosen for the units are based on local names or bird species and are a little disconcerting at first. Vegetation classes, although specific to Herschel Island, are based on common species and comparable to other more widespread classifications like the Alaska vegetation classification (Verieck et al., 1992). Published studies from Herschel Island usually translate the ecological classes into more comprehensive names (Kokelj et al., 2002) or group them based on broad characteristics (Obu et al., 2015). This report is supposed to provide baseline data for further research projects in the area and therefore the Herschel specific unit names were maintained. These names are familiar to researchers working on site and are so most accurately describe the landscape. Below are summaries of the ecological and vegetation classes found within the area of Ice Creek watershed, they are based on information of Smith et al. (1989), personal communication with I. Myers-Smith, H. Lantuit and personal observation. For a complete description of all classes, refer to Smith et al. (1989).

Vegetation Classes

Cottongrass/moss (Eriopherum vaginatum/Bryophytes)

This vegetation types can be found in the upland areas of the island that are poorly drained and active layer depths are shallow. Its distinctive feature are tussocks that are formed by the *E. vaginatum* and alternatively by *Carex lugens*. Low shrubs (*Salix reticulata, S. arctica, S. pulchra*) and different *ericaceous* species grow in the gaps between the tussocks. Moss cover is up to 70% and *Sphagnum* can be found occasionally. Unless the moisture regime changes significantly, this plant community is considered to be very stable and has reached a climax state.
Abbreviation in this report: *Eriopherum*

Arctic willow/Dryas-Vetch (Salix arctica/Dryas-Astralagus)

This vegetation class is very common across the gently undulating landscape on the island. The prominent soil type is Orthic Turbic Cryosol with areas of exposed soil. It is however, not frequently found in regions of mesic to moderate erosional disturbance although open ground can be up to 80%. The most prominent plant species are *Dryas integrifolia*, various *Bryophytes* and the most common low shrubs are *S. arctica* and *S. reticulata*. Many small sized forbs occur in

this class but do not necessarily contribute significantly to the overall vegetation cover. This vegetation class is thought to be very stable and can be regarded as a climax community.
Abbreviation in this report: *Dryas*

*W*illow/ Saxifrage- Coltsfoot (Salix/Saxifraga-Petasites)

This vegetation class usually occurs in moist seepage sites or valley bottoms on moderately to imperfectly drained Turbic Cryosols. The terrain is usually moderately eroded but the vegetation forms a continuous cover. In most sites, the low shrubs *S. arctica* and *S. reticulata* co-dominate the terrain. But *Petasites frigidus* and *Equesitum sp*. can be present in high densities. This vegetation class occurs in highly dynamic areas of the landscape where sediment deposits or slumping are common.
Abbreviation in this report: *Petasites*

Arctic Willow/ Lupine – Lousewort (Salix arctica/Lupinus – Pedicularis)

This vegetation class is associated with irregular, hummocky terrain on gentle to steep slopes. The dominant shrub is *S. arctica* but *S. reticulata* is also common. A great variety of forb species can be found on the hummocks, such as *Dryas integrifolia* and *Lupinus arcticus*. Areas between the hummocks are dominated by moss. Due to the instable terrain this vegetation class is constantly evolving and with changing erosion rates or moisture it can develop into other vegetation classes such as chamomile-grass or saxifrage-coltsfoot.
Abbreviation in this report: *Salix-Lupine*

Grass/Chamomile – Wormwood (Gramineae/ Matricaria-Artemesia)

This plant community establishes on recently disturbed terrain with gentle to very steep slopes. Open ground can be up to 75% and the active layer is often deep due to high soil accumulation from upslope erosion. Different graminoid species such as *Alopecurus alpinus* and *Arctagrostis latifolia* dominate in the vegetated areas. *Salix arctica* may be present and some of the most common forbs are *Artemesia tilessii* and *Senecio congestus*. It is the earliest successional stage after disturbance.
Abbreviation in this report: *Chamomile*

Shrub Zone

This vegetation/ecological class was added by I. Myers-Smith in 2014. The class is characterized by a high density of stall standing shrubs like *Salix richardsonii*. The shrub zone is somewhat comparable to the shrubby flood plains on Herschel Island. However, the newly defined Shrub Zone is often drier and not necessarily associated with hydrophilic plants like

Eriophorum angustifolium. Instead, other plant species found are often similar to the surroundings outside of the Shrub Zone such as *S. arctica*, *S. reticulata*, *Equesitum sp*. and *Petasites frigidus*.

Abbreviation in this report: *Shrub*

Ecological Classes

Guillemot

Guillemot is associated with polygonal ground on poorly drained soil with high organic matter content. The vegetation cover depends on the moisture regime and the sedges in the wettest areas accumulate to peat. The Guillemot class is only found in the northernmost tip of Ice Creek West and will not be discussed further.

Herschel (HE)

The Herschel unit is typical for poorly drained upland plateaus. No other vegetation type than *Eriopherum* can be found in these areas. The main soil type is Turbic Cryosol and the pH is low because of weathering and base leakage. Cryoturbation may sequester organic matter and disturbances through ground ice thaw can create non vegetated scars. The shallow active layer depth makes it very thaw sensitive.

Figure 2: Herschel ecological class. Soil profile on the left and landscape view on the right. Pictures taken in early August 2014 by AWI Herschel field crew.

Komakuk(KO)

Komakuk is the most common land cover class on Herschel Island. It is more diverse than the Herschel unit but also a very stable community. Active layer depth is up to 50cm and soils mostly Turbic Cryosols with an imperfect drainage. Most of the Komakuk terrain is covered with the *Dryas* vegetation class.

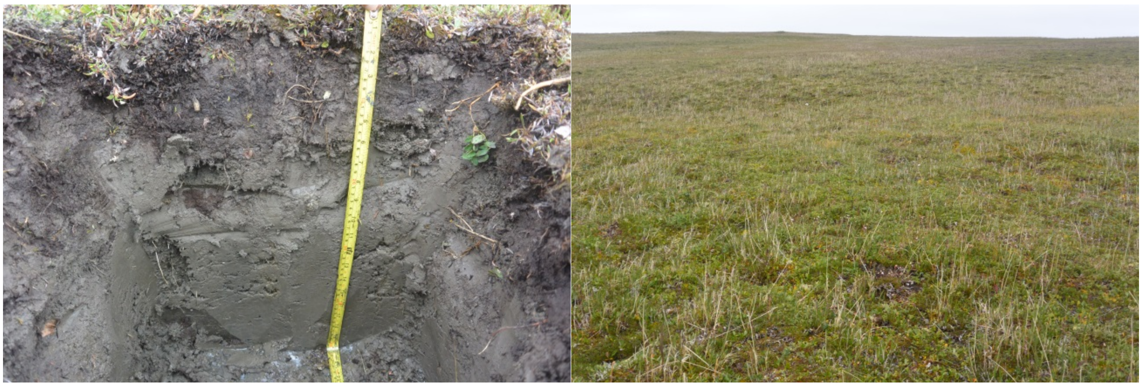


Figure 3: Komakuk ecological class. Soil profile on the left and landscape view on the right. Pictures taken in early August 2014 by AWI Herschel field crew.

Plover-Jaeger (PJ)

The Plover-Jaeger class is actually comprised of two separate units. Plover only occurs in few areas as defined though extensive patterned bare ground but is difficult to distuinguish from Jaeger in the field. Obu et al. (2015) revised the land cover map from Smith et al. (1989) and joined them together. This ecological class is typical for moderately eroded and very varied terrain. Due to the spatial heterogeneity, the vegetation cover is very diverse. Mass movement processes expose bare ground and active layer depth can be variable. Typical vegetation classes are *Dryas* for the less disturbed and *Salix-Lupine* for the more disturbed sites.

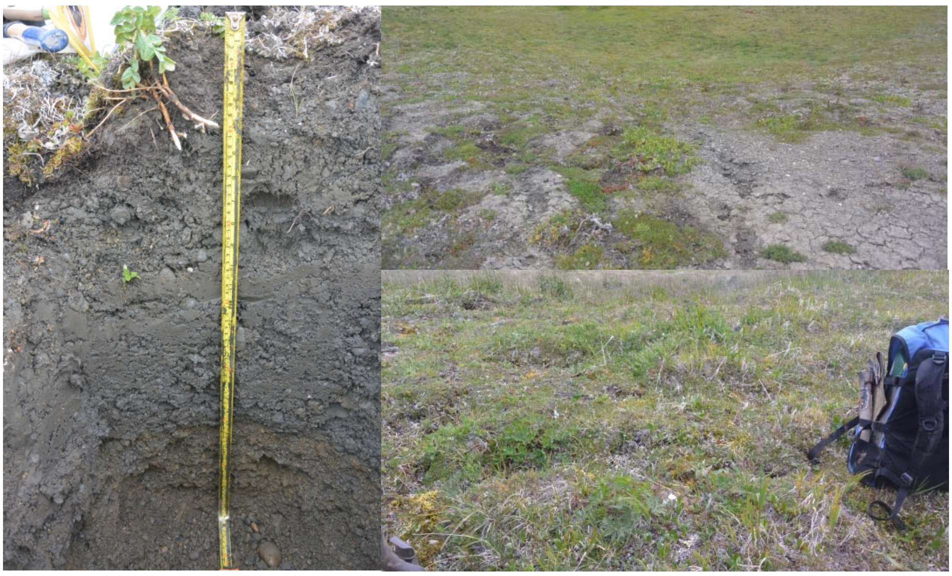


Figure 4: Plover-Jaeger ecological class. Soil profile on the left and landscape view on the right. Pictures taken in early August 2014 by AWI Herschel field crew.

Thrasher (TH)

The Thrasher unit can be found on steep slopes or highly disturbed terrain. Solifluction, retrogressive thaw slumping, active layer detachments and other instabilities are common for this class. The soils are of regosolic character and exposed sediments are often of marine origin and rich in calcareous material. The soils are usually well drained but their properties can be variable depending on the erosional material. Vegetation regrowth usually is similar to the *Chamomile* class and in less eroded terrain *Salix-Lupine* dominates.

Figure 5: Thrasher ecological class. Soil profile on the left and landscape view on the right. Pictures taken in early August 2014 by AWI Herschel field crew.

Shrub Zone (SZ)

For the description of the Shrub Zone refer to the vegetation class with the same name.

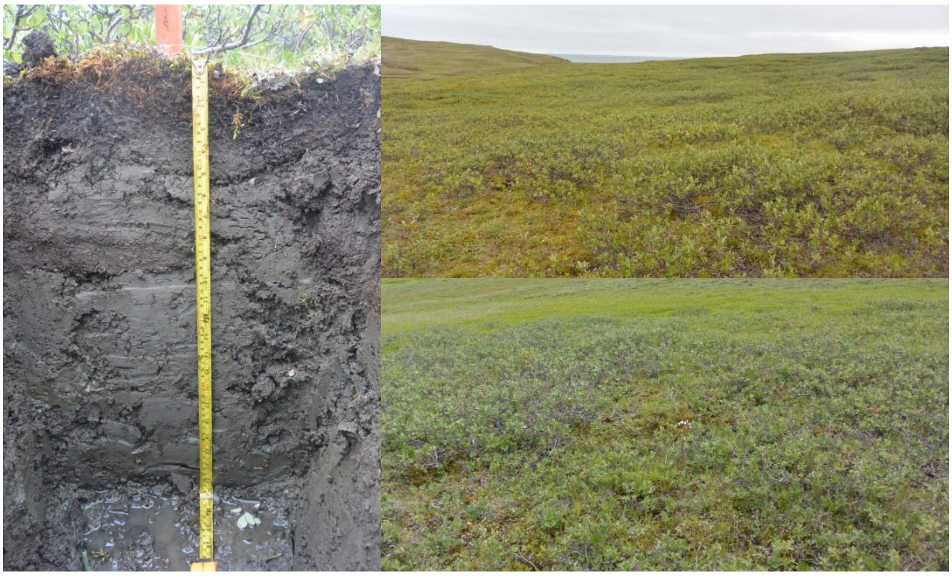


Figure 6: Shrub Zone ecological class. Soil profile on the left and landscape view on the right. Pictures taken in early August 2014 by AWI Herschel field crew.

Wet Terrain(WT)

The Wet Terrain class was added by I. Myers-Smith in 2014 to properly characterize the areas that are close to the creeks and subject to regular flooding or on seepage sites along the slopes. Fluvial processes and erosion may frequently deposit new material. A high degree of soil accumulation forms a deep active layer. The dominating plant species can vary. *Petasites frigidus* and *Equesitum sp.* are very common. This class is mainly associated with the *Petasites* vegetation class.

Figure 7: Wet Terrain ecological class. Soil profile on the left and landscape view on the right. Pictures taken in early August 2014 by AWI Herschel field crew.

3. Methods

3.1 Study Site

Herschel Island

Herschel Island (or Qikiqtaruk) is situated at 69°36′N; 139°04′W, in the northwest corner of the Yukon Territory, Canada. It is a terminal moraine that formed during the Buckland Stage of the Wisconsinan Glaciation, which pushed out of the Herschel basin (Mackay, 1959; Lantuit & Pollard, 2008). It is 108 km^2 and has a maximum elevation of 128 m. The landscape is characterized by soft, undulating hills with few very steep slopes. A few exceptions are the (mainly coastal) retrogressive thaw slumps and active layer detachments that are typically steep and lack vegetation cover (Smith et al., 1989). Sediments are fine and of marine origin (Smith et al., 1989). It is located in the biogeographical subzone "B: Low Arctic" which is characterized by the presence of tundra vegetation including shrubs, but an absence of trees (AMAP, 2007). In winter the climate on Herschel is influenced by the ice sheet surrounding it and the air is cold and dry. In summer, climate is more maritime and therefore moist and comparatively warm (Rampton, 1982, Fritz, 2008). Between September and May, temperatures lie below 0 °C and highest the temperatures reached between June and August are around 18 °C but mostly below 10 °C (http://climate.weather.gc.ca/).

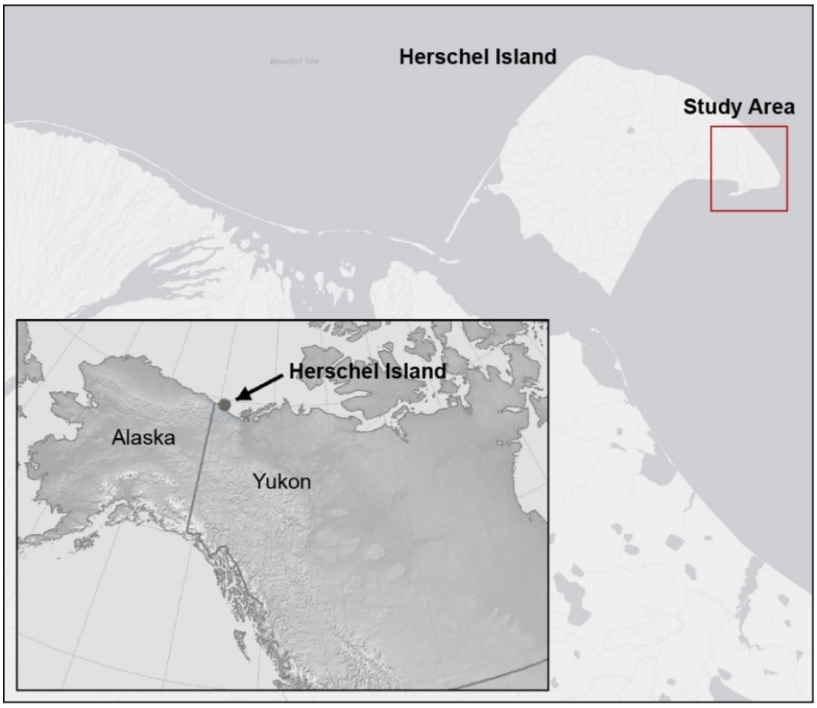
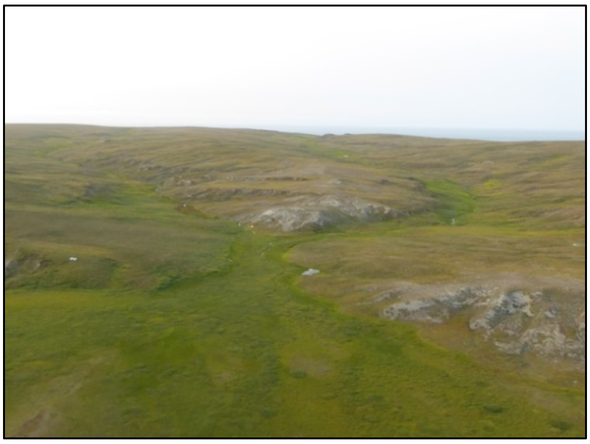


Figure 8: Location of Herschel Island (69°36′N; 139°04′W) situated at the border between Alaska and the Yukon.

There are many periglacial features and processes on Herschel Island. These include, ice wedges, ice wedge polygons, earth hummocks, non-sorted patterned ground, as well as solifluction lobes (Smith et al., 1989). All of Herschel Island is underlain by continuous permafrost and active layer depth is seldom deeper than 50 cm, but can reach depths greater than one meter (Smith et al., 1989, personal observation). Soil formation is often influenced by mass movement along slopes and through freeze-thaw cylces. The most common soil taxon is therefore the Orthic Turbic Cryosol (Smith et al., 1989).

Ice Creek watershed

The Ice Creek watershed is made out of two separate watersheds, Ice Creek East and Ice Creek West. Because the streams share a confluence the entire area is generally referred to as Ice Creek watershed. For the purpose of this thesis, Ice Creek encompasses both watersheds unless it is stated otherwise. The watershed is situated in the southeast corner of Herschel Island and drains into a fluvial plain before entering the Beaufort Sea. Maximum elevation within the watershed is 180 m and can be regarded as a typical watershed on the island. Gully erosion, solifluction lobes and new as well as old active layer detachments are present within the area (Smith et al, 1989). Ice Creek West and East are similar in size (West: 1.4 km^2, East: 1.6 km^2). They have a similar landform, although Ice Creek East contains a small lake in its upland and slopes along the creek are slightly steeper.



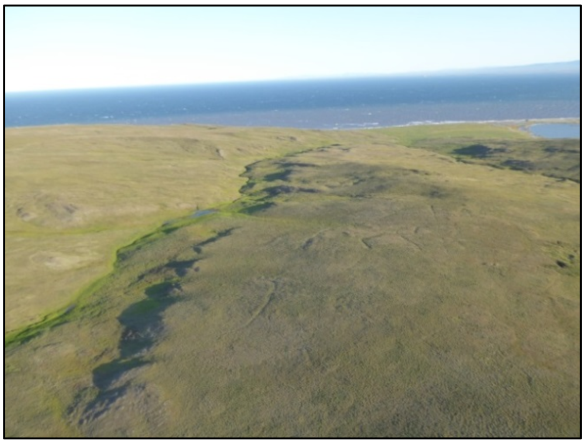


Figure 9: left: Ice Creek East and West confluence, facing north. right: Ice Creek East uplands, facing south. (I.Eischeid, 06.08.2015)

3.2 Selection of Sampling Locations

Remote Sensing

In 2014, active layer sampling locations were chosen based on two criteria, 1) the different ecological classes present on Herschel Island, and 2) and equal spread throughout the watershed to obtain representative information about soils and vegetation. The watershed delineation was calculated from a 2x2 meter digital elevation model (DEM), using the confluence of Ice Creek East and West as the pour point with ArcGis 10.3 (ESRI). The ecological classes used as reference were the classification from Smith et al. (1989) and the updated ecological classification map from Obu et al. (2015). Three 100 meter wide transects were drawn to represent the upper, middle and lower section of the watershed each covering all the ecological classes most prominent in the Ice Creek watershed. Within those transects five random points from each ecological class were chosen. To avoid atypical sections, areas with a slope greater than two standard deviations away from the mean of that class were excluded. The five locations were then manually ranked based on suitability. Suitable sampling sites were characterized by a good spread across the transect, as well as being as far away as possible to the boundaries of other ecological units to avoid edge effects. See figure 10.

Ground Truthing

In 2015, a preliminary watershed classification map from the 2014 was used to randomly select 20 ground truthing points to validate the accuracy of the classification. Ground truthing locations were chosen such that all the ecological classes were sampled at least once. Location names were saved without the predicted class label to avoid bias during field assessment.

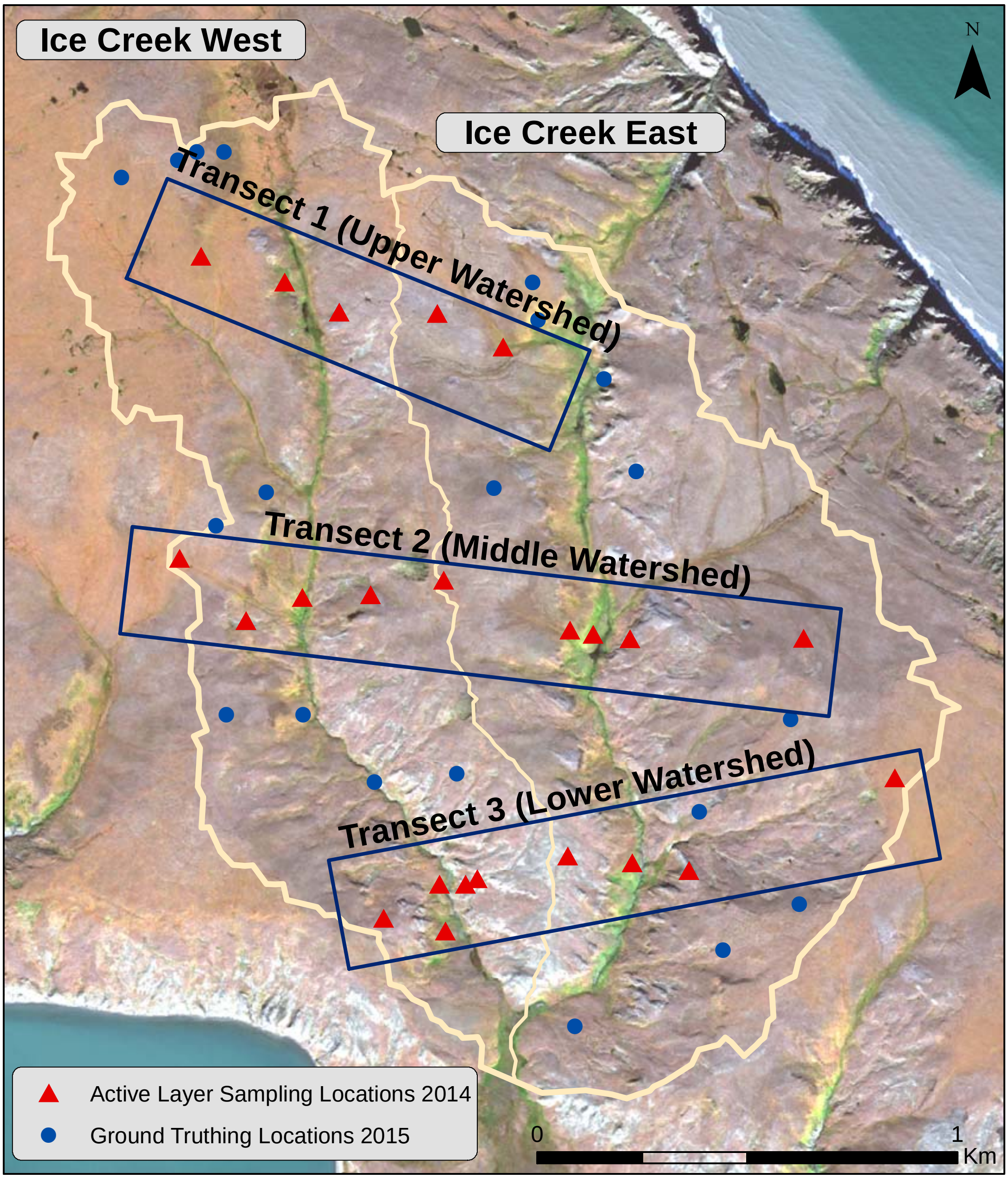


Figure 10: Overview of the study area, Ice Creek West and East. Located in the South West corner of Herschel Island

3.3 Field Work

Field work was undertaken by members of the AWI Potsdam team and Shrub Ecology group at Edinburgh University between the 31.07.2014 and 06.08.2014. Handheld GPS (Garmin eTrex HCx) were used to find the sampling sites. A reassessment of the classes was done in the field and three new classes, Shrub Zone, Herschel-Komakuk and Wet Terrain were added because none of the previous classes were able to describe the habitat properly. Therefore, the 23 sampling locations came from the following ecological classes: Herschel (HE) n=3, Herschel-Komakuk (HK) n=1, Komakuk (KO) n=4, Plover-Jaeger (PJ) n=5, Thrasher (TH) n=2, Shrub Zone (SZ) n=2, Wet Terrain (WT) n=6. At each location 50 cm wide soil pits were dug until the permafrost table was reached. Three horizontal undisturbed soil samples (214 ml) were extracted at the depth of 5-11 cm, 15-21 cm and above the permafrost boundary using a core sampler (for practical reasons in some sites measurement intervals were slightly shifted downwards). Samples where immediately bagged and brought to a field lab facility. Within one day of sampling, conductivity, pH, and wet weight were measured and the samples were stored in a cool dry place until being transported. The bagged active layer samples were brought to Potsdam (Germany) at cool but ambient temperatures and stored in a cooling room until further assessments were conducted.

Vegetation assessments were done at three different locations within 10-15 meters of the soil sampling site. At each location a 50cm x 50cm frame was placed on the ground to estimate plant species cover and measure canopy height. Each time, two people estimated plant species and bare ground cover and the value was averaged.

Between 09.08.2015 – 11.08.2015, twenty ground truthing sites were visited. Locations were found using a handheld GPS (Garmin eTrex HCx). The ecological class, the vegetation class, and the most prominent plant species were noted for each site.

3.4 Image Processing

Aerial image

For all remote sensing analysis of this study, a GeoEye image was used. Of the available images at AWI Potsdam, the GeoEye image has the highest resolution (1.65m) and is therefore the most suitable for the fine scale landscape analysis of this study. The image was taken on 08.09.2011 at 21:13 GMT. The nominal collection azimuth was 220.6 degrees and the nominal collection elevation was 82.2 degrees. Percent cloud cover was zero. It is important to note that the image has been taken three years prior to the field assessments and at a later time in the season. Colors and vegetation cover observed through the areal image taken in September may therefore be different to those that would be seen at the time of field work (July – August).

Atmospheric Processing

The GeoEye image had to be edited to remove atmospheric effects changing the spectral reflectance values of the land surface. Geomatica (PCI Geomatics 2014) was used for this process. For this particular image only small corrections were necessary. Haze masking was applied and the atmospheric reflectance was removed. Furthermore, the DEM (2x2m) available for the area was used to calculate the ground reflectance (ATCOR). DEMs allow for corrections of errors induced by elevation and differing distances to the satellite that takes the image; as well as aspect and slope that will also change ground reflectance due to shading.

Georeferencing

The GeoEye image had not been fully geo referenced. Geomatica with the function 'Ortho Engine' was utilized to rectify the image. Four ground control points (GCPs) were provided by Lantuit & Pollard (2008). The image was adjusted using a 'rational function model' as it is most suitable for GeoEye images. Together with the GCPs, the rational function removes the distortion of the image by correlating pixels and ground locations. It incorporates the information of longitude, latitude and elevation and further considers the angle and position of the satellite and therefore creates an referenced image suitable for further spatial analysis (Toutin, 2004).

3.5 Remote Sensing

Training Units

Training units were created to link land cover units with spectral information. The training units were comprised of the 23 sampling locations. Around each sampling location a 10m circle was drawn in ArcGIS to create a polygon that covers the area around the point. Because vegetation plots were only taken in three cardinal directions away from the sampling point, a triangle in the missing direction was cut out from the polygon. Water and wet polygonal terrain present in the study area were not captured within the 23 sampling locations and polygons were added by hand to include them as training units.

Spectral Classification

The software ENVI 5.2.1 was used to combine the DEM and GeoEye image to create a total of five spectral bands that would be used for capturing the remote sensing classes. The resolution adjusted to layer with the lowest one (DEM - 2m). At first, an unclassified remote sensing method was tried. The method does not require training units but splits the area into classes based on difference in spectral reflectance. The number of classes can be specified and ranged from 12 to 20 in this study. The different classification systems tried with the ecological classes were parallelpiped, minimum distance and maximum likelihood. Suitability of these methods was evaluated with help of pictures and experienced researchers familiar with the study area. Further, single random points were excluded from the classification and compared with the remote sensing results. The classification system that worked best for ecological classes was then also applied for the vegetation classes.

Post Processing

The resulting land cover classification was exported from ENVI to ArcGIS to edit the data. Small patches with differing classification were removed using focal statistics, keeping the most common unit (mode) within the four next neighbouring cells. Further, a boundary clean was applied to remove kinks and irregularities uncommon in nature. The same method was applied for both ecological and vegetation classes.

Ground Truthing

Usage of ground truthing points is a good method to verify the accuracy of the remote sensing technique. These points are additional data points where ecological and vegetation classes are captured but have not been used in the remote sensing process. In this study, the ground truthing points collected in 2015 were overlain with the remote sensing map and both values were extracted using ArcGIS. Therefore, for each ground truthing point there is an associated predicted and observed value.

3.6 Laboratory Methods

All soil samples were freeze dried for two to four days. Dry weight was measured afterwards to calculate dry bulk density and water content. Then, the sample was split for further preparation and analysis. An untreated subsample (50 g) was taken and will be used for grain size analysis for further research projects within AWI Potsdam. A second subsample (12 ml) was milled at 360 rpm for eight minutes in order to homogenize the substrate for precise chemical assessments and was used for total carbon (TC), nitrogen (TN) and total organic carbon (TOC) measurements.

Dry Bulk Density and Water Content

Bulk density is an important measurement to characterize the soil. It can vary greatly with grain size, land use or biological and geological processes. Bulk density is needed to translate percentage nutrient contents into densities (weight per volume). Soil bulk densities range from 0.3 g/cm in organic soils and 1.0 g/cm (fine textured soils) to 1.7 g/cm (coarse textured soils) (Brady & Weil, 1996). Bulk density was calculated as follows:

$$\rho b = \frac{m_d}{V_t}$$

$\rho b = dry\ bulk\ density (g/cm^3)$
$m_d = dry\ soil\ weight\ (g)$
$V_t = total\ volume\ (cm^3)$

The gravimetric water content gives an indication about soil moisture at the time of sampling. It can also give an indication about the kind of vegetation and landscape dynamics that can be expected (Oechel et al., 1993). It was calculated as follows:

$$u = \frac{m_w - m_d}{m_w} \times 100$$

$u = gravimentic\ water\ content\ (\%)$
$m_w = moist\ soil\ weight\ (g)$
$m_d = dry\ soil\ weight\ (g)$

Grain Size Distribution

A 50 gram subsample was wet sieved with a mesh size of 1 mm which separated the grains into *coarse* (very coarse sand and larger) and *fine* (less than 1 mm). The coarse fragment was dried at 60 C for two days and the fine fragment was dried in a dry freezer for two days. The coarse fragment was weighed and percentages of the fragment were calculated using the total dry weight.

Total Carbon, Nitrogen and Total Organic Carbon

Part of the homogenized soil sample was used for carbon and nitrogen (CN) analysis. Two replicates of 5 mg were weighed into tin boats. Soil samples as well as standard substances used as reference points, were measured with an element analyzer (Elementar vario EL III).

This analyzer works through means of catalytic combustion where carbon and nitrogen are oxidized at high temperatures and turned into their gaseous phases. The molecules are then separated by adsorption columns and measured by a thermal conductivity detector. The percent carbon and nitrogen are then calculated from the difference of the total sample weight used for combustion. For the total organic carbon (TOC) measurements, 20-100mg of homogenized sample was weighed into small crucibles. Total organic carbon is measured in a similar way to total carbon and nitrogen, only that combustion temperatures are lower, preventing non organic carbon to enter into the gaseous phase. Empty containers were used to detect background noise, which is subtracted from the overall percentages. Furthermore, standards with known carbon and nitrogen values were fitted with the measured percentages to correct for potential over or underestimation of measured values on each day. The amount of TOC and TN were measured as percentages. Information about soil density then helped to convert percentages into TOC and TN storage (kg/m^2) within the soil:

$$TOC = \frac{h\ x\ pb\ x\ TOC\ (\%)}{10}$$

$TOC = total\ organic\ carbon\ (kg/m^2)$
$h\ = height\ of\ horizon\ (cm)$
$\rho b = dry\ bulk\ density (g/cm^3)$
$TOC\ (\%) = total\ organic\ carbon\ (\%)$

$$TN = \frac{h\ x\ pb\ x\ TN\ (\%)}{10}$$

$TOC = total\ nitrogen\ (kg/m^2)$
$h\ = height\ of\ horizon\ (cm)$
$\rho b = dry\ bulk\ density (g/cm^3)$
$TOC\ (\%) = total\ nitrogen\ (\%)$

3.7 Data Processing and Analysis

All data was organized and maintained in Excel databases (Office 2010), statistical analyses and figures were coded in R 3.1.1. Spatial data was stored at processes in ArcGIS 11.3 (ESRI).

Location Properties

Some location properties were not obtained through field work but instead, using remote sensing methods. Slope was calculated using the DEM. The distance of sampling locations to the nearest creek was extracted using a flow direction raster. The normalized difference vegetation index (NDVI) was calculated using the programme ENVI. The NDVI describes the proportion of the vegetation that is biologically active and can give an indication of different plant communities and for small areas also the pheonolgical stages within the season. It is calculated as the relative strength of red to near infrared (NIR) light within a given area.

$$NDVI = \frac{(NIR - RED)}{(NIR + RED)}$$

The DEM was used to calculate the topographic wetness index (TWI) which uses slope to estimate water accumulation sites. It is calculated as follows

$$TWI = \ln(\frac{\alpha}{tan\beta})$$

α= cumulative upslope area draining through a point
β= slope angle at that point

Both NDVI and TWI had already been calculated for the same project area and were therefore not redone for this report.

Soil Characteristics

At each location samples were taken at different depths and had to be converted into a single value representing the overall soil quality at each location. For most characteristics, solely the value of the top most core was taken (conductivity, pH, moisture, bulk density and percentage of coarse fragments). TOC and TN (kg/m^2) contents of soil in between sampling depths were extrapolated to the equal distance between them. TOC and TN values (kg/m^2) where then determined by adding the extrapolated measurements to the depths of 30 cm (global comparison standard) and the limit of the active layer. They will sometimes be abbreviated to TOC/TN-30cm and TOC/TN-active. The CN ratio was calculated as the proportion of TOC to TN. In this thesis it is referred to as CN and values in figures are displayed as the fraction of TOC over TN (TOC/TN).

Vegetation Data

The vegetation data was processed for analysis in three ways. First, using the vegetation percentage cover and with the aid of pictures, vegetation classes were assigned according to the descriptions of Smith et al. (1989). Second, for community analyses, only records of forbs and shrubs were used (feces, litter, moss cover etc. were removed). And third, for NMDS analysis plots with no vegetation cover were removed and for PCA analysis all three plots at one location were added together.

Boxplots for Ecological and Vegetation Classes and Watershed

Because sample sizes within classes, the variation of TOC, TN, CN ratio and active layer depth were displayed using simple boxplots. One set of boxplots was created with ecological classes and, for comparison; the same settings were used for vegetation classes. Furthermore all values from each transect were grouped together and compared via boxplots.

NMDS

NMDS is short for non-metric multidimensional scaling. It uses ranks of similarity or dissimilarity to group sampling locations with more similar characteristics closer together. It is a multidimensional approach but is usually displayed as a two dimensional graph. The stress indicates how well the data was fitted into the given dimensions. A value of 0.3 indicates that the arrangement is arbitrary, 0.05 would be a good fit. Statistical tests, like simper analysis, can quantify the uniqueness of different sampling groups. For this study, an NMDS was chosen as an alternative method to avoid the reducing diverse plant communities into simple classes that would have been necessary to create boxplots. Each vegetation plot was taken as a separate unit (n=66) and percentage covers were used to compare the community structures. The resulting points in ordination space were labelled to which ecological class they belong. This allows for a qualitative assessment, on how well differences in plant communities align with ecological classes.

PCA

PCA is short for principal component analysis which is a statistical method to analyze correlations of multiple variables together and place them in a multidimensional space. It is usually displayed in a two dimensional grid where the first and second axis are the ones explaining most of the variation within the data. Sampling locations with similar characteristics will be placed closer together. Vectors representing the factors are fitted within the ordination space. They can give information about redundancy among variables if they are oriented in the same direction. Further, the direction and strength of the vectors gives an indication which factors are important at explaining the different characteristics between sampling points.

For this study, the following soil and location characteristics were included in the PCA: active layer depth, organic horizon depth, bulk density, coarse fragment percentage, moisture, percentage of bare ground and litter, slope, NDVI, distance to the creek, TOC, TN, CN ratio within the first 30cm and the entire active layer. The site characteristics vectors in line with the TOC and TN vectors would show the highest co-correlation and best describe the variation of carbon and nitrogen in the active layer of the soil. The ecological and vegetation classes were added to the plot and close grouping of all points from one class indicates that it has distinct soil characteristics such as highest moisture, intermediate NDVI and low percentage of open ground.

Landcover Comparisons

Land cover classifications for ecological and vegetation classes were compared in ArcMap 11.3 (ESRI) by using the zonal statistics tool to create a table indicating what percentage of area each class shares. By clipping the Ice Creek watershed by its East and West sections the total area of ecological and vegetation class within each area could be calculated and converted into percentages.

Further Statistical Analysis

ANOVAs in connection with Tukey HSD post hoc test were carried out to detect significant differences between different datasets. P values of <0.1 were considered significant due to small sample sizes and heterogeneous ecological data. However, all p values stated in this thesis should only be taken as orientation to detect likely differences because sample sizes were small and not normally distributed. Non-categorical data was assessed with the Spearman's rank correlation test which is a good method for small datasets that are not normally distributed (Gauthier, 2001).

4. Results

4.1 Remote sensing

Classification System

The maximum likelihood classification method (supervised classification) was selected to map the ecological and vegetation classes. This most was deemed most suitable, based on visual assessments and evaluation of the classes with randomly chosen ground truthing points. Parallelpiped and minimum distance methods created classifications that had very sharp edges unusual for natural systems and were therefore no longer considered in this study.

Ecological and Vegetation Classes

The remote sensing outputs for ecological classes were similar to the ones for vegetation classes. Typically, for each ecological class, there was a vegetation class associated with it (table 2). However, this does not necessarily mean that a certain vegetation type will be found in an ecological zone. Figures 5 and 6 underlay the similarities and differences found in the distribution of both ecological and vegetation classes.

Table 2: Association of vegetation types to ecological classes. Each column shows to what percentage a certain vegetation type can be found within the ecological class.

Vegetation class / Ecological class (correspondence in percent)	Herschel	Herschel-Komakuk	Komakuk	Plover-Jaeger	Wet Terrain	Thrasher	Shrub Zone
Cottongrass/Moss	99.5	76.6	12.8	7.4	13.4	0.1	0.0
Arctic Willow/Dryas Vetch	0.0	21.5	82.7	1.2	0.4	1.4	0.4
Willow/Saxifrage-Coltsfoot	0.4	0.0	0.3	0.6	84.1	5.9	6.0
Arctic Willow/Lupine-Forget-me-not	0.0	1.8	3.1	84.9	0.7	11.2	2.7
Grass/Chamomille-Wormwood	0.0	0.1	1.1	5.6	0.3	73.9	0.0
Shrub Zone	0.0	0.0	0.1	0.3	1.2	7.5	90.9
Total	100	100	100	100	100	100	100

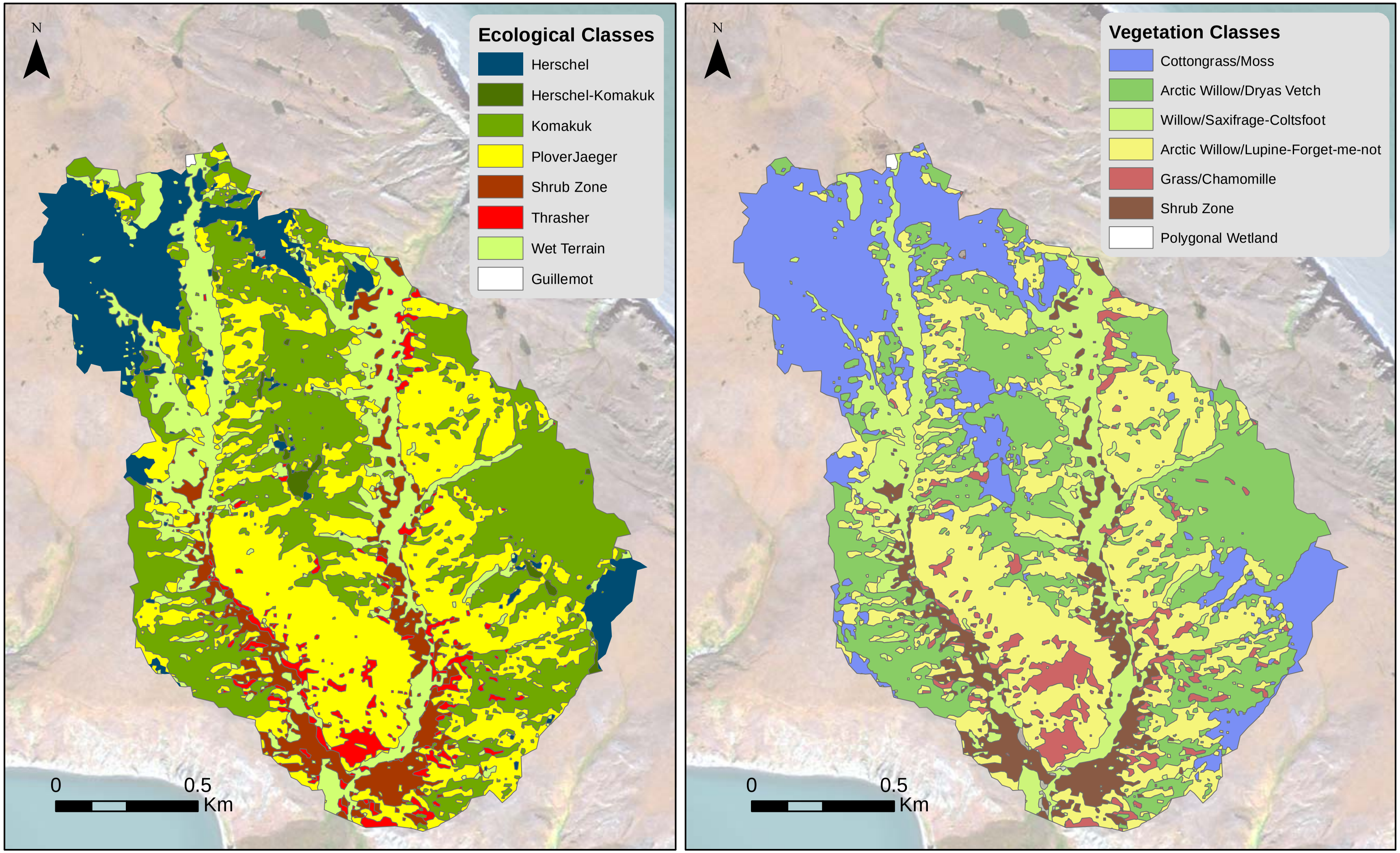


Figure 11: Classification of the Ice Creek watershed using ecological units (left) and vegetation units (right).

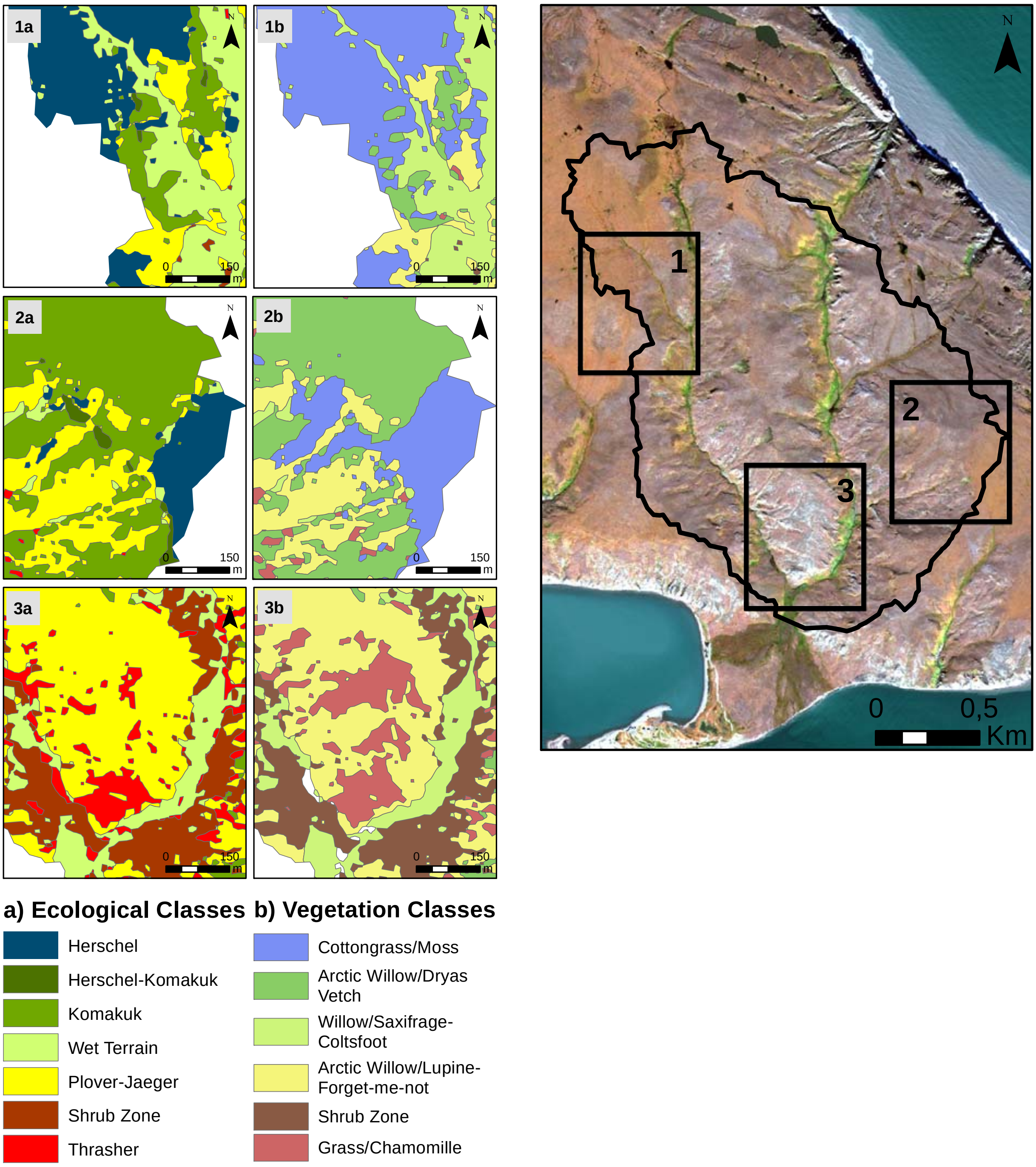


Figure 12: Highlights of study area where the vegetation type does not coincide with the typically associated ecological class. In the extents 1) and 2) Eriophorum extents further into the steeper sections of the watershed than would be suggested by the Herschel ecological class. In 3) more areas are covered by the grass-chamomile vegetation class as would be predicted by the extent of the Thrasher unit.

Ground Truthing

The ground truthing tables compare to what extent predicted classes coincide with field observations. For both the ecological as well as the vegetation classes, the prediction accuracy varied between 0-100% and 25-100% respectively. Neither classification system had a considerably higher prediction accuracy. The total ground truthing accuracy for the ecological zones was 55% and 45% for vegetation classes. The classes Herschel and Thrasher had a prediction accuracy of 100%. Thrasher was found in the field in areas where it was not detected by the remote sensing process and therefore the observer's accuracy is lower. Two thirds of the area predicted to be covered by Komakuk were covered with Plover-Jaeger instead. Inversely, areas that were found to be Komakuk were predicted to be Wet Terrain and Shrub Zone. For more information, see table 3.

The vegetation classes showed a similar pattern as ecological classes. The grass-chamomile vegetation class had a prediction accuracy of 100%. Eriophorum, usually a strong indicator of the Herschel ecological class, only had a prediction accuracy of 50%. Arctic Willow/Lupine-Forget-me-not areas were predicted to an accuracy of 60% but observer's accuracy is considerably lower because the vegetation class was found in more areas than predicted. For more information, see table 4.

Table 3: Classification accuracy between observed (ground truthing) and predicted (classification) ecological units.

predicted/ observed	Herschel	Komakuk	Herschel-Komakuk	Plover-Jaeger	Wet Terrain	Shrub Zone	Thrasher	Predictor's accuracy
Herschel	2							100%
Komakuk		1		2				33%
Herschel-Komakuk				1				0%
Plover-Jaeger			1	4			1	67%
Wet Terrain		1			1			50%
Shrub Zone		1			1	1		33%
Thrasher							2	100%
Observer's accuracy	100%	33%	0%	57%	50%	100%	67%	

Table 4: Classification accuracy between observed (ground truthing) and predicted (classification) vegetation units.

predicted/ observed	Cottongrass/ Moss	Arctic Willow / Dryas Vetch	Willow/Saxifrage-Coltsfoot	Arctic Willow/Lupine -Forget-me-not	Grass/ Chamomile	Shrub Zone	Predictor's accuracy
Cottongrass/ Moss	2			2			50%
Arctic Willow/Dryas Vetch		1		2			33%
Willow/Saxifrage-Coltsfoot		1	1				50%
Arctic Willow /Lupine-Forget-me-not	1	1		3			60%
Grass/ Chamomile					3		100%
Shrub Zone		1	1			1	33%
Observer's accuracy	67%	25%	50%	43%	100%	100%	

4.2 Ordination

NMDS

Plant communities and not vegetation classes such as the ones reported on in 4.1) did not align as clearly with the ecological classes as vegetation classes do (figure 13). The Herschel unit appeared to be a very distinct plant community. However, the Plover-Jaeger unit encompassed vegetation communities that were very dissimilar and were not to be separated from the Komakuk and most Thrasher points. The Wet Terrain and Shrub areas also overlapped with their plant communities.

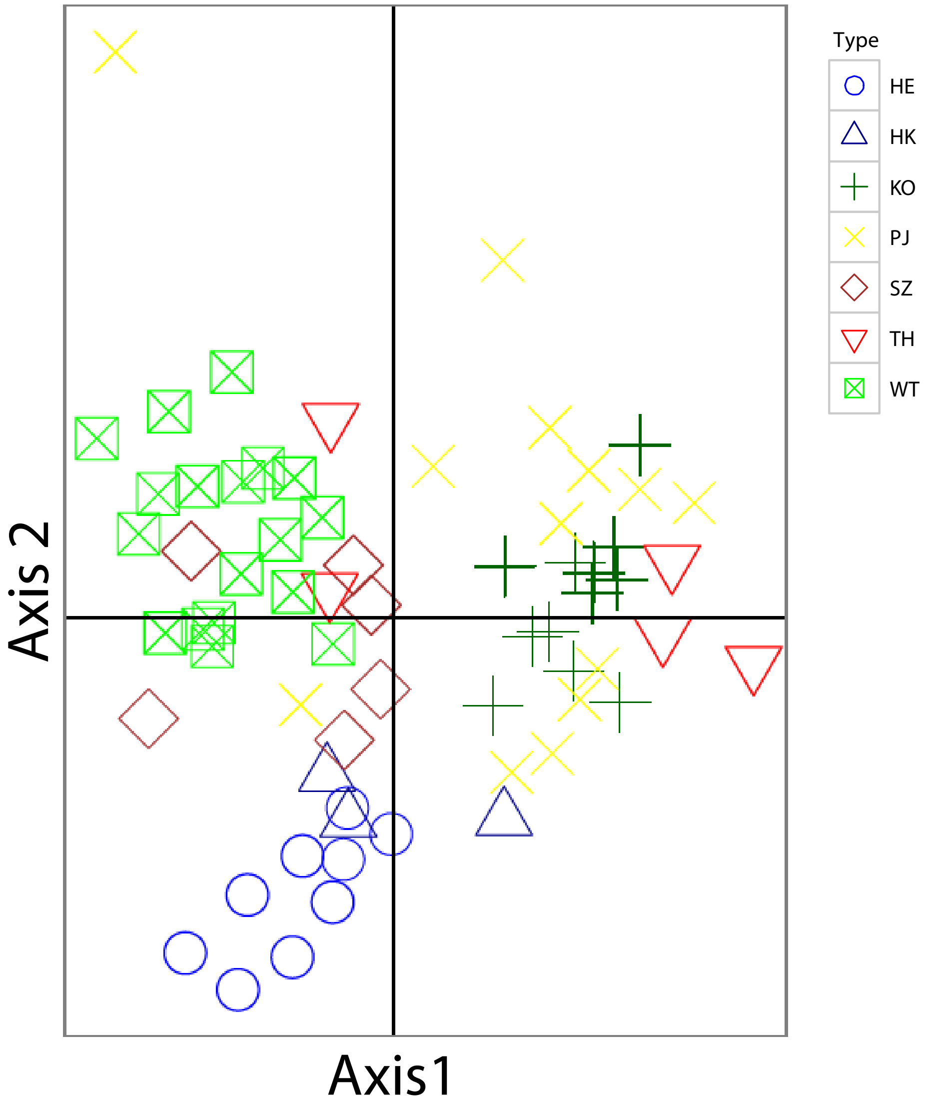


Figure 13: Non-metric multidimensional scaling (NMDS) of forbs and shrubs at 66 sampling locations. Correspondence with ecological zones is indicated by symbols and colours. Stress: 0.176. HE Herschel, HK Herschel-Komakuk, KO Komakuk, PJ Plover-Jaeger, SZ Shrub Zone, TH Thrasher, WT Wet Terrain.

PCA

The PCA included several parameters including TOC, TN and other soil properties. The PCA outputs reflected a similar picture as the boxplots. Ecological classes were not better defined than vegetation classes. Neither method created distinct groups that show no overlap with others. Plover-Jaeger had soil properties similar to Thrasher while the Herschel, Komakuk, and Wet Terrain units all had similar soil properties. The Camomile and Salix-Lupine vegetation classes both formed distinct groups and were defined by a deep active layer, high bulk density and a high percentage of bare ground. The other vegetation classes could not be clearly separated from one another (figure 15). The PCA also showed that CN ratios closely followed the same direction as NDVI and the depth of the organic horizon. Additionally, TOC down to 30cm was positively correlated to topsoil moisture and negatively correlated to bulk density, active layer depth and percentage of bare ground. TN-30cm and TOC-active showed less alignment with any of investigated soil properties. TN-active was negatively correlated to the percentage of coarse grains and slope.

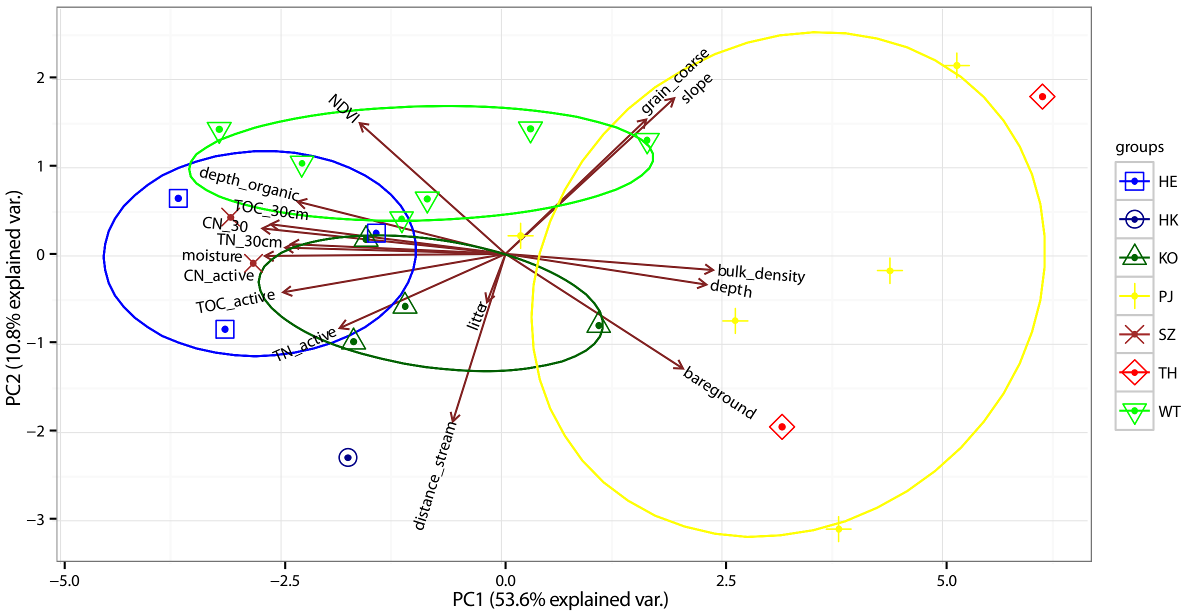


Figure 14: Principal component analysis of soil properties at 23 sampling locations with ecological classes indicated in different colours. HE Herschel, HK Herschel-Komakuk, KO Komakuk, PJ Plover-Jaeger, SZ Shrub Zone, TH Thrasher, WT Wet Terrain.

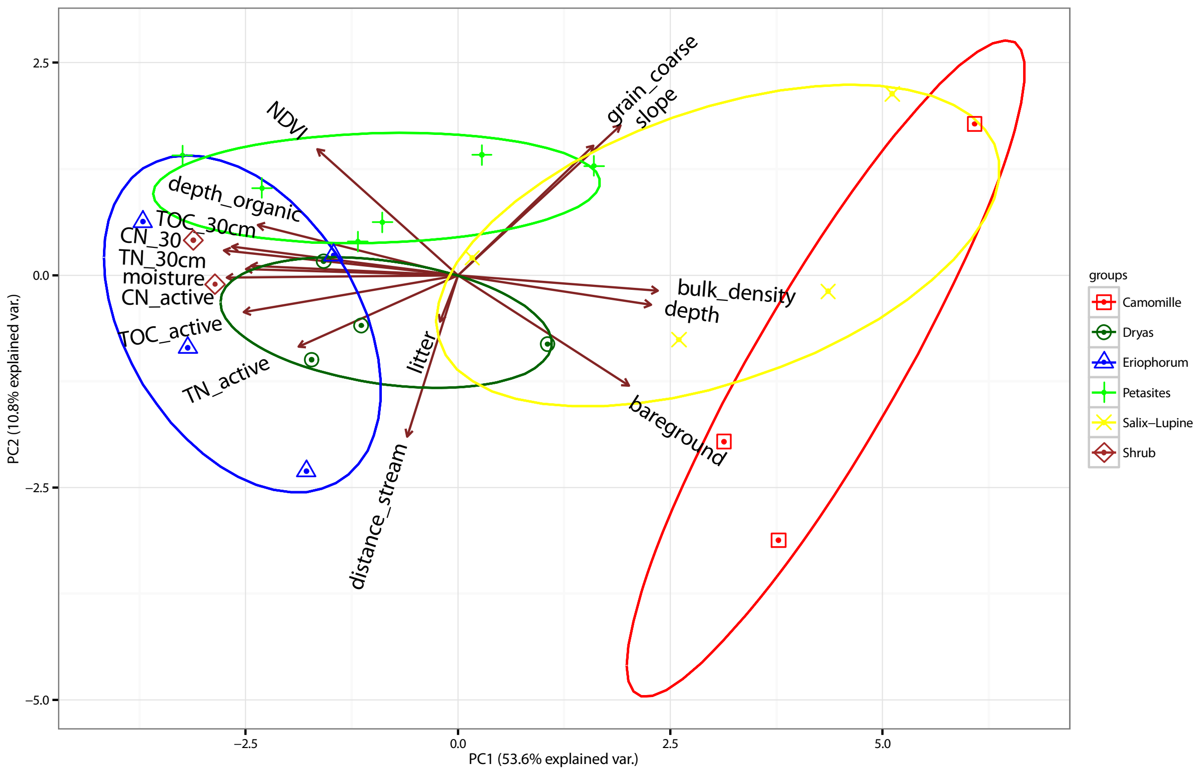


Figure 15: Principal component analysis of soil properties at 23 sampling locations with vegetation classes indicated in different colours.

4.3 Ice Creek Total Organic Carbon and Nitrogen Storage

Terrain

Generally, Spearman's rank correlations were the highest for moisture, followed by NDVI and slope. TWI was not well correlated to TOC and TN. Correlations with TN contents in the active layer as a whole were not significant for all compared parameters.

Table 5: Spearman's rank correlation (ρ) of TWI (topographic wetness index), moisture in topsoil, NDVI (normalized difference vegetation index) and slope (in degrees) with TOC (total organic carbon), TN (total nitrogen) and the CN ratio. Significance of <0.1 =* and <0.05=**.

ρ	TOC 0-30cm	TOC Active	TN 0-30cm	TN Active	CN 0-30cm	CN Active
moisture	0.74**	0.61**	0.65**	0.31	0.84**	0.73**
TWI	0.36*	0.37*	0.22	0.25	0.4*	0.44**
slope	-0.44**	-0.42**	-0.35*	-0.21	-0.43**	-0.5**
NDVI	0.48**	0.46**	0.54*	0.23	0.55**	0.5**

Ecological Classes

Total organic carbon (TOC) was not evenly distributed throughout the watershed. Sloped areas with high shrub densities (Shrub Zone) held the highest amounts of TOC. They were closely followed by flat uphill areas (Herschel Zone). The differences in TOC within the first 30cm of the soil were not as pronounced compared to the entire active layer depth . The lowest TOC values were found in recently disturbed areas (Thrasher). The distribution of TOC and nitrogen were similar and highly correlated ($r= 0.95$, $p= 9.927e^{-12}$, $df =21$). CN ratios were the largest within the Herschel Zone, followed by shrub areas. The Thrasher zones had the smallest ratio. The Komakuk and Plover-Jaeger zones were characterized by soil carbon and nitrogen contents that are intermediate compared to the zones described above, The Komakuk Zone, however. generally had higher TOC and nitrogen contents as well as a shallower active layer depth. For detailed information, see figures 16 and 17 as well as table 6.

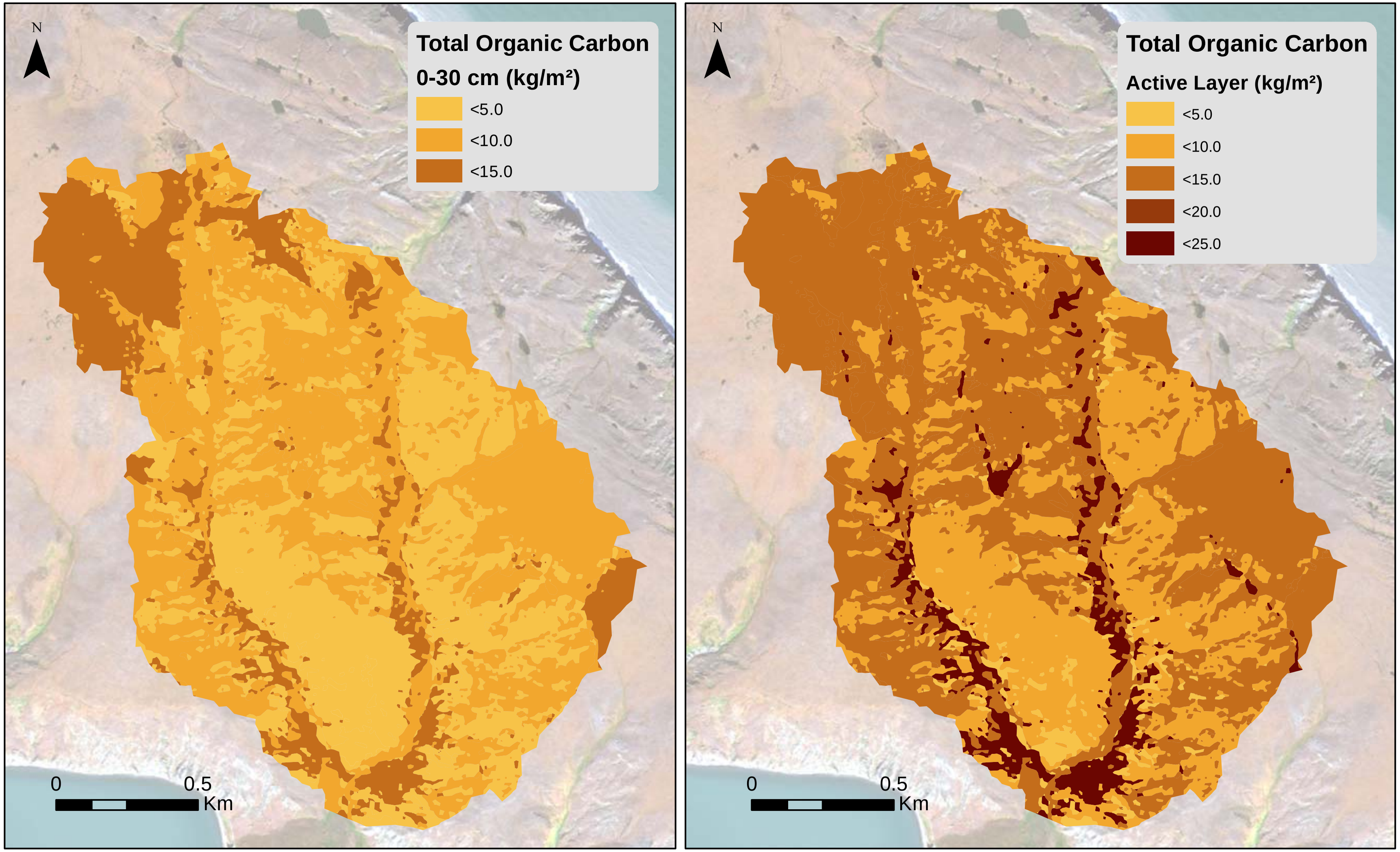


Figure 16: Total organic carbon (kg/m^2) at 0-30cm (left) and the entire extent of the active layer (right) in Ice Creek watershed on Herschel Island.

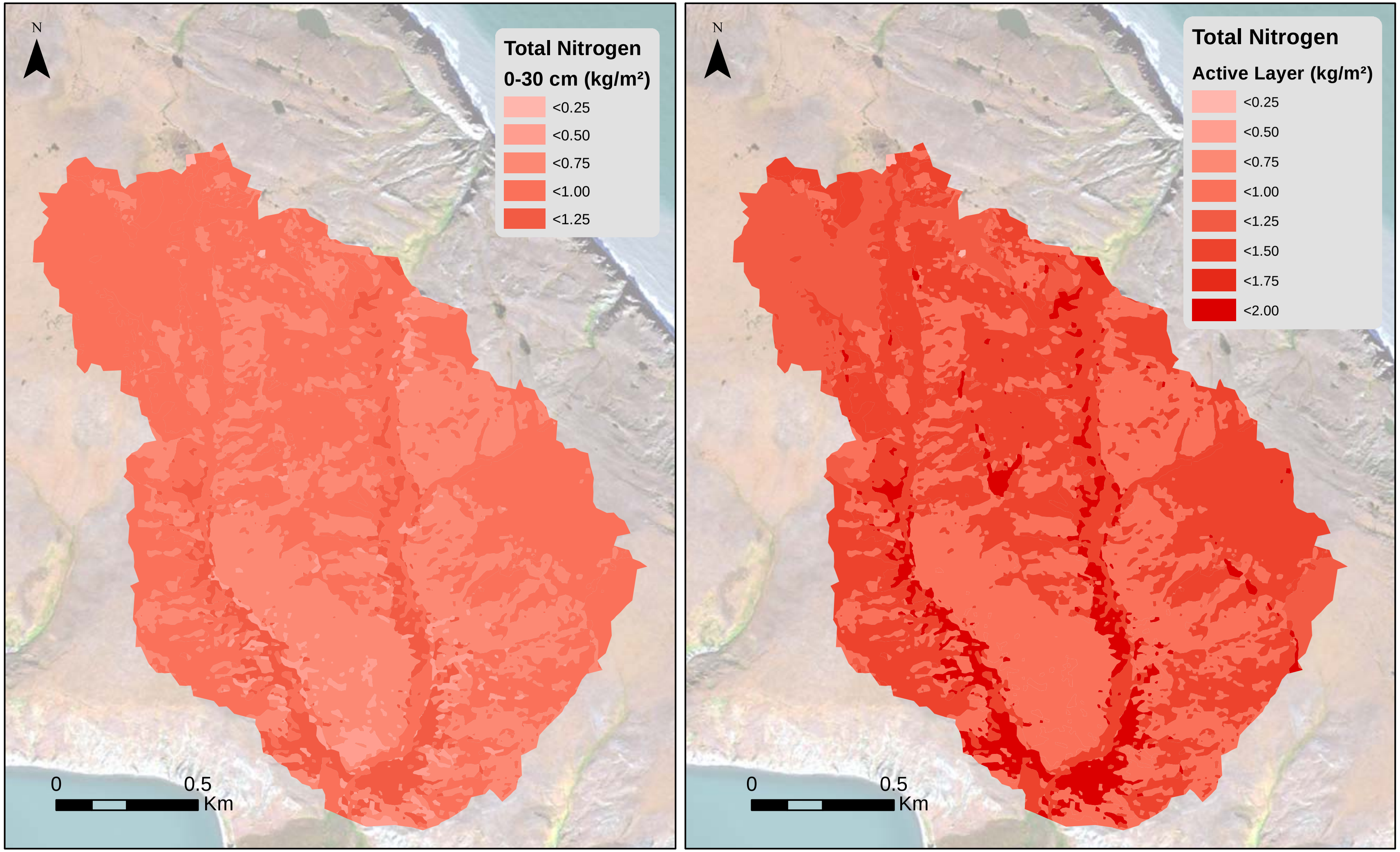


Figure 17: Total nitrogen (kg/m^2) at 0-30cm (left) and the entire extent of the active layer (right) in Ice Creek watershed on Herschel Island.

Ecological Class	Active Layer Depth (cm)	Bulk Density (g/m^3)	Moisture (%)	TOC-30cm (kg/m^2)	TOC-active (kg/m^2)	TN-30cm (kg/m^2)	TN-active (kg/m^2)	CN-30cm (kg/m^2)	CN-active (kg/m^2)	Bareground cover (%)	Slope (°)	NDVI	TWI
Herschel	35	0.52	56.60	11.91	13.96	0.88	1.05	13.66	13.44	0.00	4.53	0.70	8.98
Herschel-Komakuk	48	1.07	26.90	7.85	24.71	0.74	1.88	10.60	13.12	0.75	4.73	0.67	8.05
Komakuk	52	0.72	40.93	8.22	12.75	0.81	1.38	9.99	9.08	0.35	5.58	0.66	7.88
Plover-Jaeger	74	1.36	14.88	4.39	6.07	0.56	0.92	6.27	5.79	69.50	10.64	0.62	7.96
Shrub Zone	59	0.36	62.90	13.51	21.68	1.08	1.89	12.47	11.49	0.00	6.52	0.68	9.05
Thrasher	73	1.38	11.85	1.72	4.30	0.35	0.87	4.49	4.43	97.75	15.78	0.58	7.93
Wet Terrain	50	0.86	38.22	9.17	13.12	0.91	1.38	9.82	9.45	5.03	9.16	0.76	8.39

Table 6: Averages of soil and landscape properties for each ecological class. Carbon and nitrogen contents are highest for the Shrub Zone and lowest for Thrasher areas. Bulk density of the topsoil is highest for Plover-Jaeger and Thrasher and lowest for the Herschel class. A similar trend can be detected for topsoil moisture. Further information about active layer depth, moisture, density, TOC,TN, CN, percentage of bare ground, slope, NDVI and TWI can be obtained from the table.

Ice Creek East and West were similar in size and overall distribution of vegetation. the Herschel ecological class coverage was greater in Ice Creek West. In Ice Creek East, greater areas were covered by the Komakuk and Plover-Jaeger classes. Total storage of carbon in the active layer in Ice Creek West was 15999 tonnes and 17392 tonnes for Ice Creek East. Storage of Nitrogen was 1673 and 1962 tonnes respectively. Together, both watersheds held 22978 t TOC in the first 30 cm and 33391 t in the active layer. Nitrogen storage was 2256 t down to 30 cm and 3635 t in the entire active layer. For detailed information, see table 7.

Table 7: Comparison of area covered by ecological classes and TOC, TN storage in Ice Creek West and East.

	Ice Creek West					Ice Creek East				
Ecological Class	Percentage cover	TOC-30cm (tonnes)	TOC-active (tonnes)	TN-30cm (tonnes)	TN-active (tonnes)	Percentage cover	TOC-30cm (tonnes)	TOC-active (tonnes)	TN-30cm (tonnes)	TN-active (tonnes)
Guillemot	0.1					-				
Herschel	20.6	3435	4027	253	302	4.1	781	916	57	69
Herschel-Komakuk	0.6	66	208	6	16	0.8	100	316	9	24
Komakuk	24.4	2807	4354	276	472	37.5	4931	7648	484	830
Plover-Jaeger	29.0	1781	2463	229	375	35.6	2498	3455	321	527
Shrub Zone	5.6	1060	1700	85	148	6.4	1384	2220	111	193
Thrasher	3.0	72	181	15	36	3.1	85	213	18	43
Wet Terrain	16.7	2143	3067	212	324	12.5	1834	2623	181	277
Total		11364	15999	1075	1673		11614	17392	1181	1962

Upon visual inspection of the boxplots, neither the ecological nor the vegetation approach divided TOC or TN values into well-defined classes. For the TOC values, there was a higher in-class variance found in the vegetation classes. This variation was however, consistent for the TOC-30cm and TOC-active values. Aside for the Wet Terrain, the ecological classes at TOC-30cm created quite distinct groups but included more outliers than the vegetation classes. One very high TOC value in the Plover-Jaeger section changed the variance and average of this ecoclass greatly. The Herschel-Komakuk class was not consistent in the TOC-30cm and the TOC-active layer. In the first 30cm, the value was comparable to the Komakuk class, whereas at the entire active layer depth, TOC values were even higher than those found in the shrub zone. The high carbon content can be explained by a peaty layer found at 40cm depth. Due to the small sample size (n=1), there is no option to validate if the Herschel-Komakuk type is usually underlain by peat and if the sample analyzed here is representative or not. The spread of TN was similar to

TOC but no classes were significantly different from one another. There were no completely distinct divisions in either the ecological or vegetation classes. Within the vegetation classes, the variance did not differ notably between TN-30cm and TN-active. Within the ecological classes, there was a notably higher variance in the Thrasher and Plover-Jaeger classes for the active layer depth. For both classification systems, CN values created more clearly defined groups than TOC and TN contents.

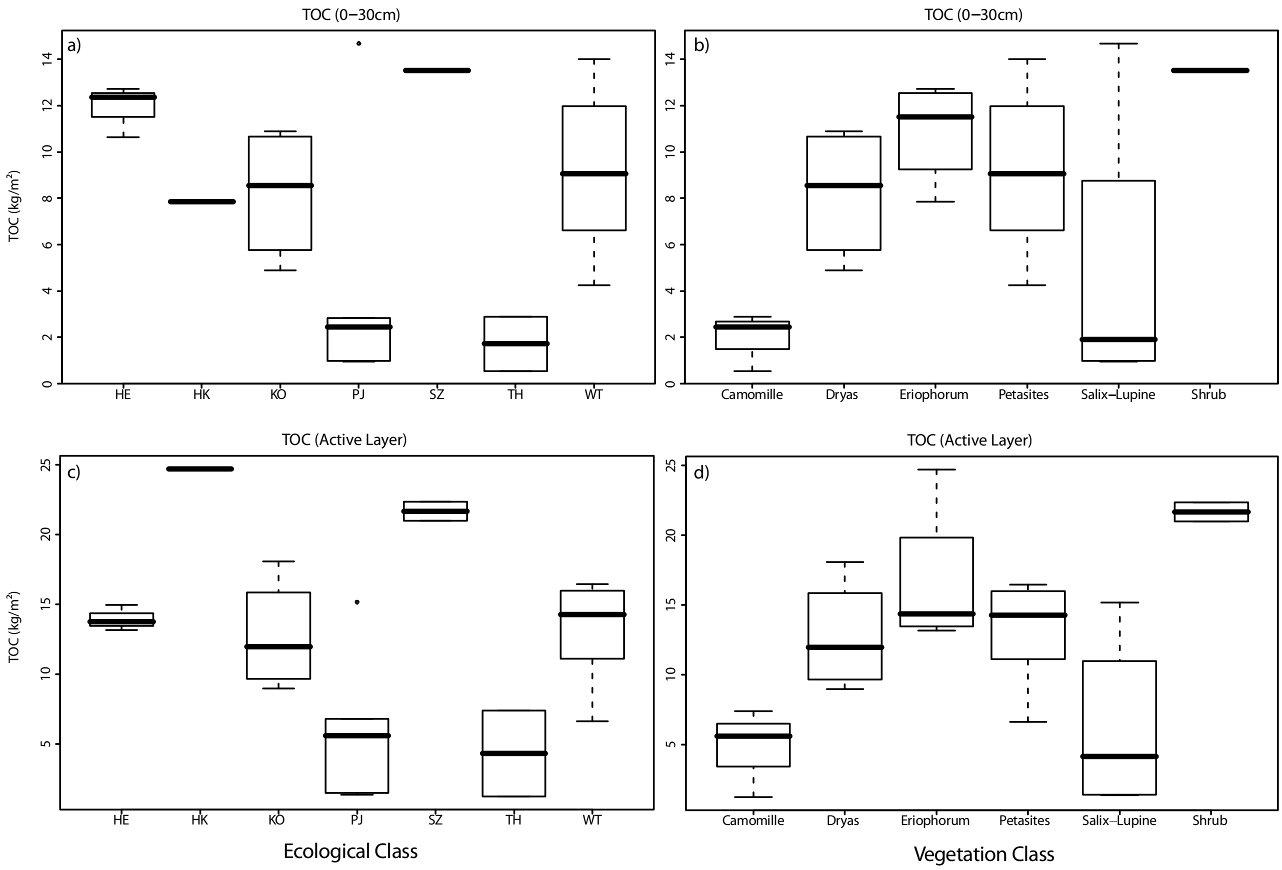


Figure 18: Comparison of TOC (kg/m²) in the first 30 cm (a,b) and the entire active layer (c,d) of the soil between ecological and vegetation classes. Significant differences occur between a) TH-SZ p= 0.079 b) Eriophorum-Camomile p= 0.059, Shrub-Camomile p= 0.036, c) PJ-HK p= 0.011, TH-HK p= 0.013, SZ-PJ p= 0.0048, TH-SZ p= 0.0089, d) Eriophorum-Camomile p= 0.033, Shrub-Camomille p= 0.0089, Salix-Lupine-Eriophorum p= 0.047, Shrub-Salix-Lupine p= 0.012, df(ecoclass)=6, df(vegclass)=5. HE Herschel, HK Herschel-Komakuk, KO Komakuk, PJ Plover-Jaeger, SZ Shrub Zone, TH Thrasher, WT Wet Terrain.

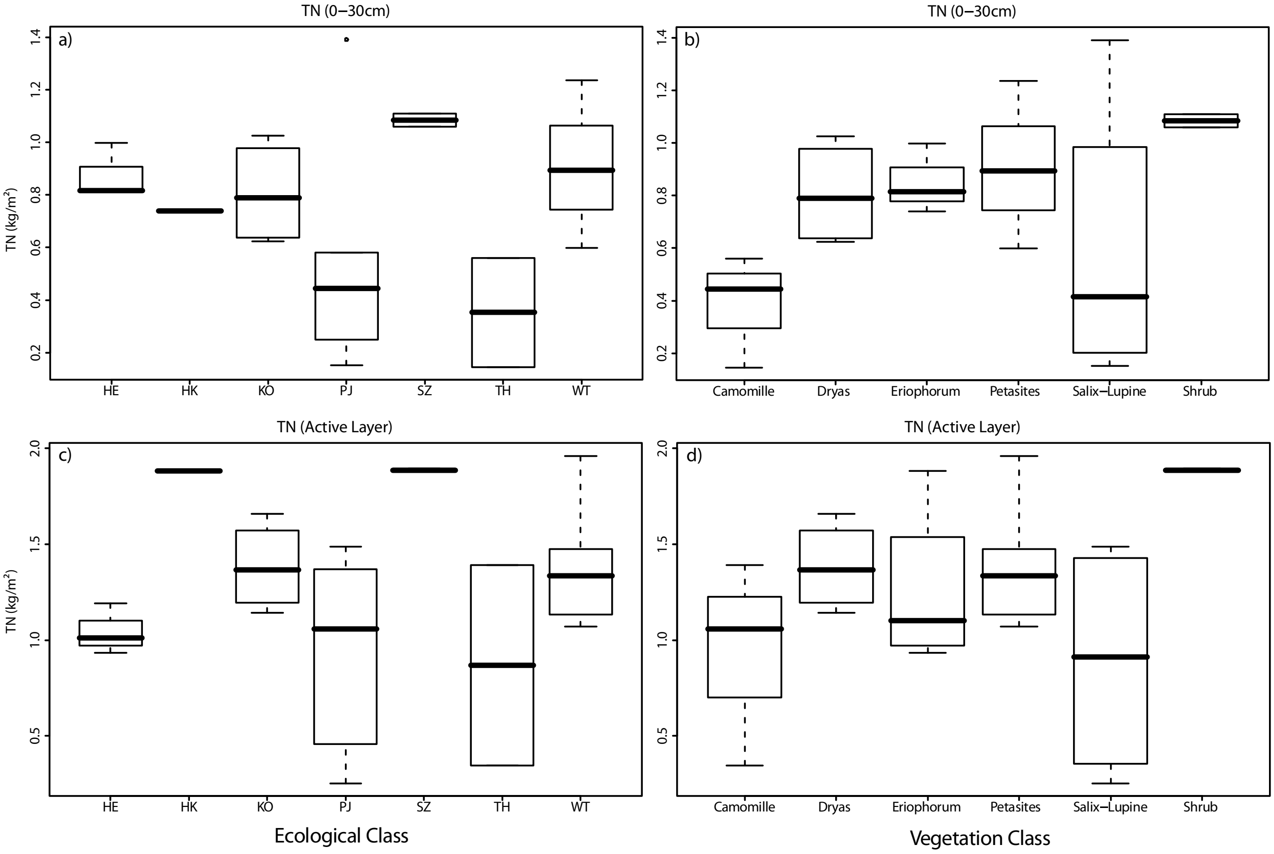


Figure 19: Comparison of TN (kg/m^2) in the first 30 cm (a,b,) and the entire active layer (c,d) of the soil between ecological and vegetation classes. No significant differences occur between the different ecological or vegetation classes. HE Herschel, HK Herschel-Komakuk, KO Komakuk, PJ Plover-Jaeger, SZ Shrub Zone, TH Thrasher, WT Wet Terrain.

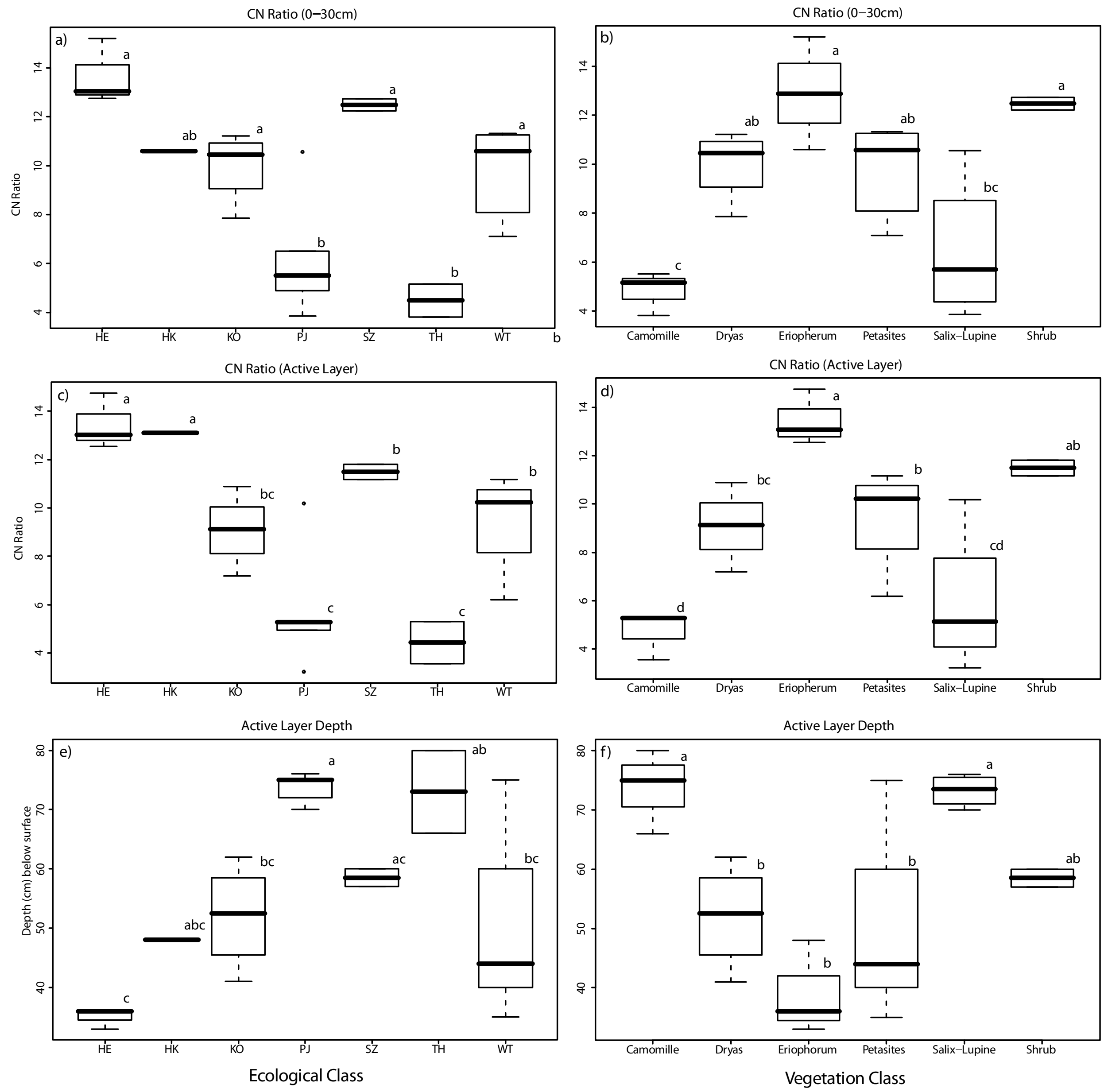


Figure 20: Comparison of CN ratios in the first 30 cm (a,b,) and the entire active layer (c,d) of the soil as well as active layer depth (e,f) between ecological and vegetation classes. Significant differences (p=0.1) are indicated by different letters besides each plot. HE Herschel, HK Herschel-Komakuk, KO Komakuk, PJ Plover-Jaeger, SZ Shrub Zone, TH Thrasher, WT Wet Terrain.

Transects

Figure 21 illustrates the distribution of TOC contents within the three transects surveyed in the field. For information about the exact positions of the transects, refer back to figure 10 in the methods.

In the upper transect, the creek did not form a very deep incision and slopes were gentle. The amount of carbon present in the soil did not vary much between different catenary positions. Total active layer depth, in comparison to the first 30cm, did not add considerably more carbon. This can mainly be attributed to shallow active layer depths. The general pattern in the middle and lower watershed was that high elevation sites had high TOC content in the first 30 cm but similar to the upper transect locations, active layer depth was shallow and TOC-active did not add much carbon. In locations that were not on the flat uplands, the soil below 30 cm contributed at least as much carbon as the first 30 cm. There was no linear trend of TOC contents decreasing toward the stream. Instead, high upland TOC contents were followed by lower values on slopes and increased again in proximity to the stream. In three locations (one in the middle transect, two further downstream) TOC contents were extremely low in both the first 30 cm and deeper.

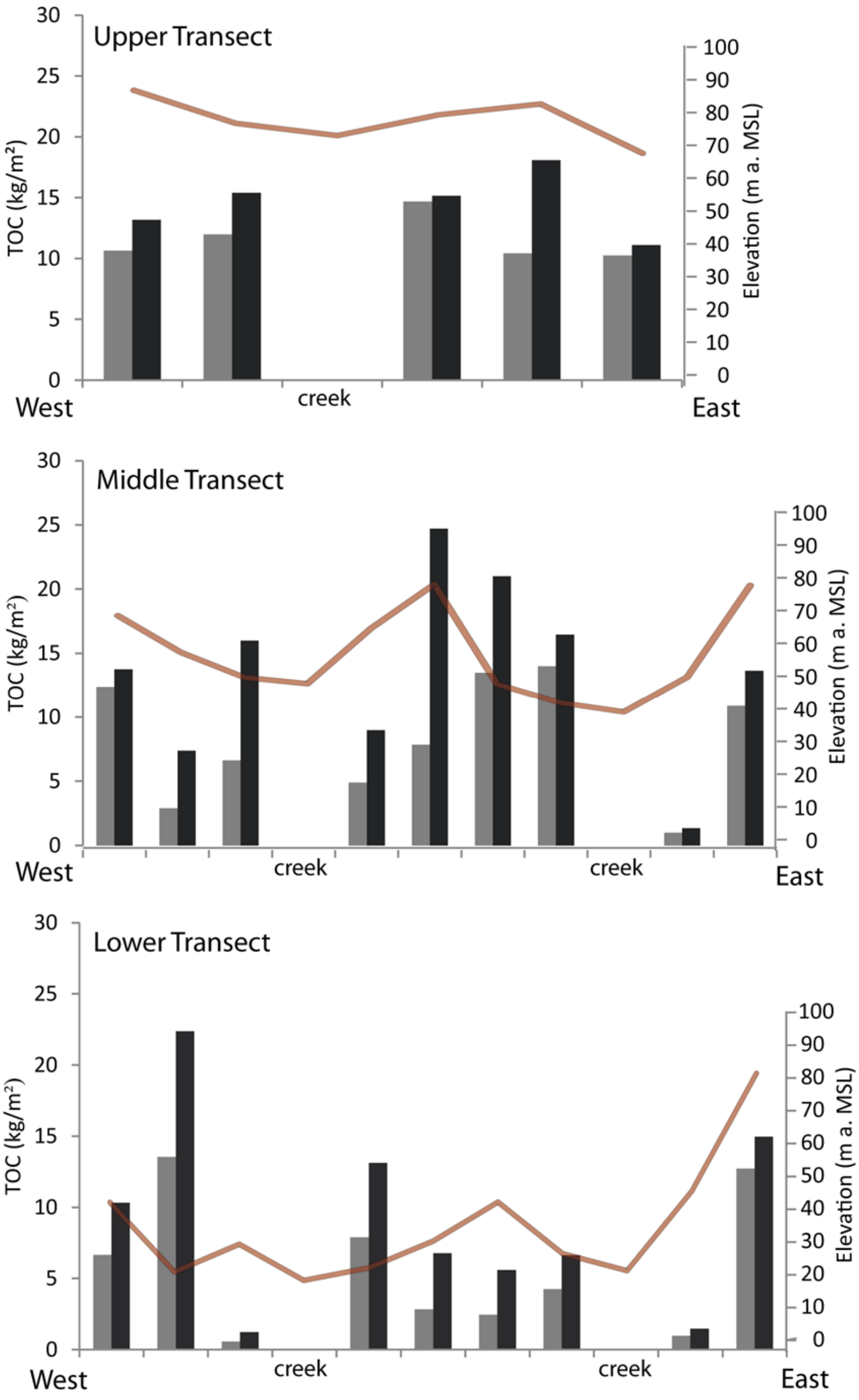


Figure 21: Total organic carbon (kg/m^2) at each sampling point on three transects across the Ice Creek watershed. Histograms in light grey: TOC (0-30cm), in dark grey (TOC-active). The line indicates the elevation of each sampling location. Distances between points on the x axis are not to scale. Additional elevations outside of sampling locations are not included, additional ridges and valleys may therefore been overlooked. The upper transect only passed through Ice Creek West.

The soil (0-30cm) in the upper and middle transects held more TOC and TN compared to the transect in the lower reach of the watershed (fig. 22a,b). This difference was smaller, and statistically not significant, when the entire active layer depth was taken into account. Statistically significant differences were found for TOC (0-30cm), p=0.065 (upper-lower transect) and TN (0-30cm), p=0.051 (upper-lower transect), df=22. CN values were much greater for the upper areas of the watershed. The difference in CN ratios became more pronounced if only samples sites directly situated by the stream were taken into account (fig. 22d- CN Ratio Creek). Because of their discrete nature, however, TOC and TN boxplots for stream adjacent sites are not shown in the figures. Significant differences for creek proximal sites were found for TOC (0-30cm), p=0.039 (upper-lower transect), TN (0-30cm), p=0.071 (upper-lower transect) and CN, p=0.063 (upper-lower transect), df=9.

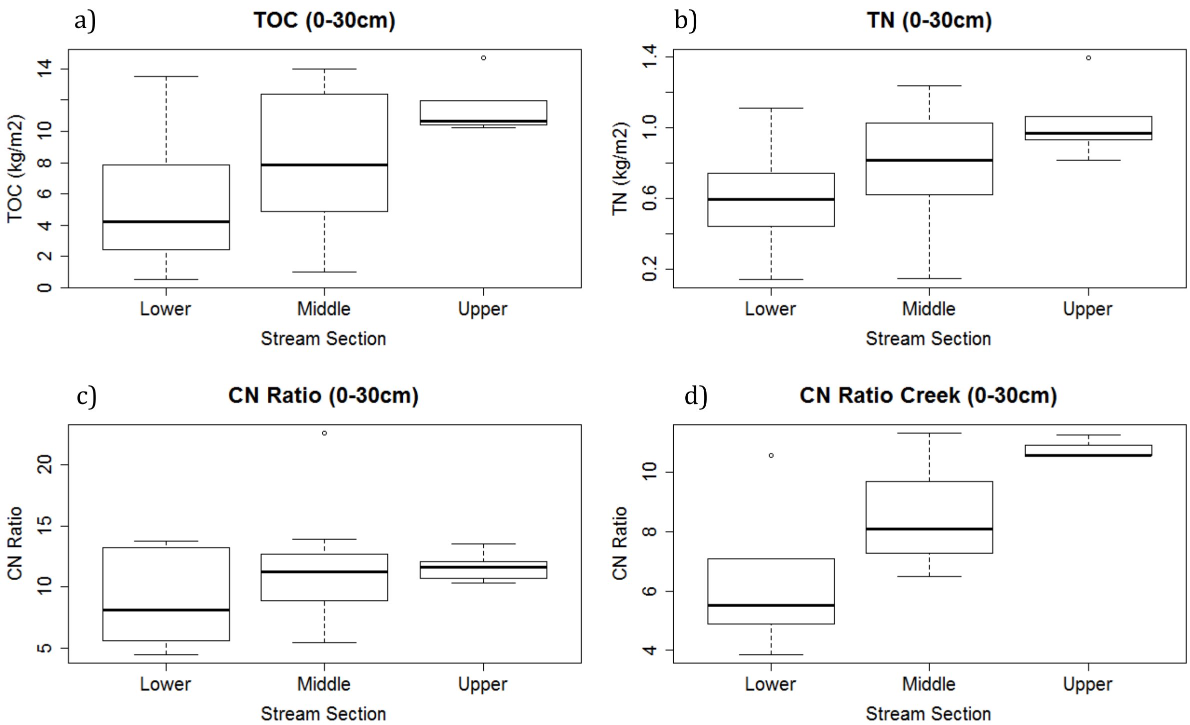


Figure 22: Boxplots comparing the differences in TOC, TN and CN ratios between an upper, middle and lower transect within the Ice Creek Watershed.

5. Discussion

The main goal of this study was to create a fine scale map with organic carbon and nitrogen estimates for both Ice Creek watersheds. The objective was also to understand spatial patterns in the distribution of soil organic carbon and nitrogen to help future studies that will look at fluvial discharge and sediment flows within the watershed. The first section of the discussion will evaluate the detectability of land cover classes and how well the classification systems characterize the soil. The second part will investigate how the spatial distribution of soil organic carbon and nitrogen is related to terrain. Information on terrain, ecological classes and the transect-based investigation will then be brought together to assess active layer characteristics of the Ice Creek watershed. Finally, the implications of the overall and spatial storage of soil organic carbon and nitrogen for potential fluxes of organic matter from the Ice Creek in the face of a changing climate will be addressed.

5.1 Remote Sensing Classification

Detectability

Motive

A common approach to upscaling organic carbon (TOC) and nitrogen (TN) from single soil pits to larger areas is by using land classification maps. Landscape classes chosen because they explain soil properties well may, however, not be easily identified through remote sensing (RS) techniques if the classes spectral image properties are too similar. The defined RS classes would ideally require few training sets to reduce field work and be detected using different image types. The idea is that the classes are spectrally distinct enough that it is possible to correctly predict the occurrence of these classes in an unknown (so far unclassified) area. Depending on the spread and the information behind the data, different classification algorithms might group the classes best. The expected prediction accuracy will depend greatly on the spatial resolution of the project (McKenzie & Ryan, 1999).

Evaluation

In this study, a maximum likelihood classification was deemed to be the most suitable method. This method was compared to other ones and selected based on an accuracy assessment conducted with ground truthing points collected in the field, as well as input from experienced researchers familiar with the study area. Maximum likelihood also has the advantage to allow for comparisons with other RS carbon estimate studies (Hugelius et al., 2010; Hugelius et al., 2012; Zubrzycki et al., 2013). Randomly excluding training units to use them as ground truthing points works well when there are enough training units available. But when there are too few, important information for the classification will be lacking. Finding the balance of an adequate number of training units and enough validation points is a common dilemma for map makers (Young, 2008). At the time of the conception of the classification system, ground truthing points collected in summer 2015 were not available and this explains the limited use of ground truthing points to evaluate the most suitable method.

The finalized classification maps were, however, evaluated for accuracy with the ground truthing points taken in 2015. Neither ecological (55%) nor vegetation classes (45%) had a high overall ground truthing accuracy and were much lower than in other, comparable, studies (78%. Hugelius et al., 2012; 77% Zubrzycki et al., 2013; 75% Obu et al., 2015,). However, some of these studies (e.g. Hugelius et al., 2012) considered ground truthing point to be positive if at least one pixel within a 5 m radius was matching. In this study, a positive match was only recognized if the majority of the pixels within a 3 m radius corresponded.

Although the accuracy was slightly higher for the ecological classes, they did not perform better overall. Some classes had an accuracy as low as 0% and contributed to lower the overall accuracy considerably. The mixed class, Herschel-Komakuk, which only occurred in very small areas, is the main source of inaccuracies and it is not different enough from the others to be properly detected by the RS system. The highest ecoclass ground truthing accuracies were found in the “extreme” classes: undisturbed Heschel areas and the highly disturbed Thrasher. This suggests that the RS system was good enough to capture landcover differences linked to vegetation density but struggled to define differences in areas with similar species but different community compositions. Obu et al. (2015) also pointed out that classification accuracies were much lower between the intermediate classes on Herschel Island. The difficulty in distinguishing between vegetation types at this scale becomes even more apparent with the vegetation class approach. Only the grass-camomile unit (usually linked to areas with bare ground) had a prediction accuracy of 100%. Shrub areas were not well detected (33%), which was unexpected given that their structure and colour may differ substantially, and they have been detected well in other studies (Hugelius et al., 2012).

One of the reasons for the low prediction accuracy might be the selection of training units. The training units for this project were atypical because there were several training units for the same class. Other projects often have only one, but very representative, training unit per class (Obu et al., 2015).

Independent of the training units, the chosen spectral bands might also have been insufficient to capture the classes well. GeoEye images are not commonly used for arctic land cover assessments. The spectral bands incorporated for this study where from 0.45μm to 0.92μm, the colours from blue to near-infrared. These four bands, however, do not describe the whole range of reflective properties of the Earth’s surface. Non reflective data can be added to enhance the classification. In this project, a DEM was added to the four GeoEye bands. Because the four GeoEye bands mainly give an indication of the absence of vegetation, the DEM was included in order to add a topographic component to distinguish between areas in the uplands or on steep slopes. The good fit of ecological and vegetation classes with the Normalized Difference Vegetation Index (NDVI) values suggests the other spectral bands do not add much value to the classification. The GeoEye picture was taken in September and late snow melt terrain appears to be very active compared to other areas. A picture taken in early summer might therefore lead to different results for these areas.

Other remote sensing based carbon estimation projects in the Arctic have included more spectral bands. For example, Zubrzycki et al. (2013) included bands 1-5 and 7 from an Landsat-7 ETM+ image. However, these spectral bands only have a resolution of 30 meter and would therefore be not appropriate for the fine scale assessment of a small watershed (Beylich & Warburton, 2007). Tasseled cap functions are often used to evaluate complex ecological data by combining different Landsat bands (Kauth & Thomas, 1976). Values like greenness, wetness and brightness can be derived from these, which have been used to monitor climate driven change in the Arctic (Fraser et al., 2012). Tasseled cap calculations are usually also based on Landsat images and therefore do not have the resolution necessary for assessing the Ice Creek watershed.

Other types of sensors could provide more information about the land surface. Synthetic Aperture Radars (SAR) can estimate moisture to a 10cm depth and could therefore aid in capturing fine scaled differences in vegetation cover (Wagner et al., 2008). How well these radar measurements reflect moisture measurements on the surface is an ongoing subject of study which could be valuable to improve our mapping approach.

Effectiveness of Classification

Motive

If a class (for example vegetation class) can be successfully detected through RS systems it has to fulfill at least two other criteria: 1.) these classes should make some ecological sense, and 2.) these classes should be valuable estimators of organic carbon (TOC) and nitrogen (TN) in the soil (most importantly in this study). The high variation in TOC and TN within one class may be based on the ecology of the class and deemed to be acceptable, but it could also imply that the classes were not chosen well because they cover too many different landscape types. For this study, high variance within one class was considered acceptable as long as overlap to other classes was minimal. Additionally, classes that had the same average TOC or TN values but were ecologically distinguishable were also considered true classes. However, due to small sample sizes and heterogeneous soils, conclusions drawn from statistical tests may be limited, and personal judgement may at times be the most useful method for assessing goodness of fit for each class. Comparable studies that classified TOC based on remote sensing used predefined classes and accepted similar means between and high variation within classes (Burnham & Sletten, 2010; Hugelius et al., 2014; Fuchs et al., 2015). This shows that the effectiveness of classification has no standardized evaluation method.

Evaluation

Ecological vs. vegetation classes:

When assigning land cover classes in the field, in most cases each ecological class corresponded to one specific vegetation class. Smith et al. (1989) suggested a strong link between ecological and vegetation classes. However, in their report, Plover-Jaeger units were less coupled to the Lupine vegetation class, as it is the case in this study. Due to their similarity, the described ecological and vegetation class approaches should not be regarded as two independent classification systems. This should be kept in mind when comparing land cover maps, boxplots and principal component analyses (PCAs) because differences are going to be inherently small.

The data collected in this study indicates that the vegetation class approach may be too simplistic to assess plant communities. The non-metric multidimensional scaling (NMDS) analysis signaled that the ecological and vegetation classes were not as similar as suggested above. Plant communities found in the Plover-Jaeger and Thrasher plots varied the most. Some Thrasher plant communities could not be differentiated from Wet Terrain plots. Furthermore, on a community level, Komakuk could not be distinguished from Plover-Jaeger and Thrasher. The NMDS plot suggested only three, maybe four (one of the shrub locations was somewhat distinguishable) vegetation classes. The NMDS evaluated all vegetation plots independently without ranking any species as more important than others. The outcomes here suggest that the vegetation classes described in Smith et al. (1989) do not describe the plant communities as a whole but instead are constructed on the base of few indicator species, like *Lupine* for disturbance and *Petasites* for wet terrain. These indicator species imply some judgement on functional groups (disturbance, wetness, early colonization) and would therefore explain the high connection with the ecological classes. Thus, a plant classification system that does not rely on indicator species would have been a better independent comparison to ecological classes.

Despite their similarities, there is an added value to comparing vegetation and ecological classes as defined by Smith et al. (1989). The ecological classes are the standard system used for many research projects on Herschel Island and should therefore be evaluated for its meaningfulness. Theoretically, they should be best at predicting soil properties because they already include information on vegetation, slope and disturbances. The vegetation classes are a reasonable alternative to predict soil properties. They include some judgement on important indicator species or functional groups but are easier to identify in the field because they require less knowledge about terrain and cryo-processes. Furthermore, they are more standardized and better suited for communication and comparisons with studies in other regions.

Which classification system describes soil properties better?

Upon visual inspection of the boxplots, neither the ecological nor the vegetation approach divided TOC or TN values better into distinct classes. Generally, variance within classes was lower for the 30 cm than the entire active layer measurements. This implies that the image based (GeoEye) remote sensing approach was better at describing topsoil properties and could only describe to a small extent, the deeper layers of the soil. Even high intensity sampling schemes, used for precision farming, struggle to detect properties at 10cm below the surface (Adamchuk et al., 2004). This challenge becomes especially apparent with the high variation of nitrogen values in the deep sections of the highly disturbed Thrasher and Plover-Jaeger units. CN values corresponded best to the proposed ecological and vegetation classes and even more so when taking the depth of the entire active layer into account. In other words, both ecological and vegetation classes were good predictors of active layer CN ratios, but did not estimate TOC and TN as correctly. Other studies that estimate TOC over larger areas with more distinct landscape types did not have lower variation within their classes. Burnham & Sletten (2010) used predefined NDVI ranges from the Circumpolar Arctic Vegetation Map (CAVM) and accepted a high variance of TOC within these NDVI classes. Hugelius et al. (2014) and Fuchs et al. (2015) employed Landsat images and maximum likelihood classification to upscale their TOC predictions and their classes' TOC values were overlapping. Therefore, albeit far from perfect, ecological and vegetation classes used for Herschel Island were decent estimators for TOC, TN and CN; especially because they were able to distinguish within vegetation communities that were grouped together in the studies mentioned above.

Although the focus of this study was to estimate soil TOC and TN, other landscape properties might give insight into how well the classification systems describe the environment. The comparative PCAs were meant to explore these properties. They show that the gradient of TOC and TN was also linked to soil moisture, active layer and organic horizon depth as well as percentage of bare ground. Ecological as well as vegetation classes were both reflected in these gradients but neither classification system was better than the other at describing the landscape properties.

Outlook

Although both classification systems did well to describe the differences in CN ratios, the TOC and TN estimates would need to be optimized. Because vegetation classes did not perform significantly better than ecological classes (the currently common method), it is recommended that ecological classes be kept as the standard procedure for Herschel Island terrain descriptions. Ideally, a clear key that uses indicator species and easily detectable terrain features should be developed to make them more recognizable in the field.

The RS assessment of the Ice Creek watershed was conducted at a very high resolution. Depending on the purpose of the data, optimization could take two different directions.

For upscaling, some classification groups that were not clearly defined through distinct TOC or TN ranges could be combined. For example Wet Terrain, Komakuk and the Herschel Komakuk zone represent a different vegetation and ecology but because they have similar TOC and TN average values, for large scale TOC and TN estimates these may be grouped together. Most studies that estimate soil organic carbon in the Arctic use classifications that are relatively broad. Obu et al. (2015) also worked on Herschel Island and did not consider Wet Terrain, Shrub Zone or Herschel-Komakuk as a separate class and achieved a remote sensing accuracy of 75%. Hugelius et al. (2012) only distinguished between peatlands, forest, willow and tundra and achieved a prediction accuracy of 78%. Using one index, like NDVI or TWI to estimate TOC and TN has been successful elsewhere (Burnham & Sletten, 2010; Obu et al., 2015). NDVI would be a potential candidate for upscaling from Ice Creek, but low correlations of TWI suggest that this is only an appropriate method for low resolution estimates.

Alternatively, for fine scale remote sensing of Arctic terrain, the estimates of TOC and TN could be further improved. Groups with similar TOC and TN values should remain separate if there is an ecological reason, for example identifiable through different vegetation types, behind it. The next step would be to explain the variance within classes to achieve higher prediction accuracy.

Instead of trying to correlate terrain factors with the entire dataset, these factors (such as slope or moisture) could be assessed for each class separately. Even low overall correlations to either moisture, slope or NDVI do not eliminate the possibility that they could still be factors to consider when optimizing TOC and TN predictions within single classes. For example, the two locations on highly disturbed terrain (Thrasher) contained considerably different amounts of TN where one was on flat ground (1.39 kg/m^2, 4.8°) and the other one on steep terrain (0.344 kg/m^2, 26.8°). Samples within the Wet Terrain also displayed a large range of soil moisture (21.1-56.9%), which correlated well with TOC-30cm contents.

5.2 Spatial Distribution of Total Organic Carbon and Nitrogen

The overall goal of this project was to quantify and describe the spatial distribution of TOC, TN and CN within the Ice Creek (IC) watershed. Despite that IC East and West have different composition of ecological classes, they have very similar total carbon and nitrogen storage within the active layer (TOC West: 15999t, East: 17392t, TN West: 1673t, East: 1962t). Although TOC and TN contents were slightly lower in IC West, the area is also smaller and per unit area IC East has marginally higher storage than IC West.

The TOC estimates from Ice Creek were, in general, comparable to other arctic studies. Hugelius et al. (2010) reported between 6.0-20.6 kg/m^2 TOC (0-30cm) for shrub tundra in the Tulemalu Lake region, where the lowest TOC values were found in the dry and the highest in the wet areas. In the Lena River Delta, TOC stocks of 13.0 kg/m^2 were reported for the active layer depth which is comparable to what has been found for the Wet Terrain unit in this study (Zubrzycki et al., 2013). Active layer nitrogen contents found by Zubrzycki et al. (2013) were on the other hand almost three times smaller (0.5 kg/m^2 TN) than what was found in the Wet Terrain of Ice Creek and even smaller than the lowest values in the highly disturbed Thrasher terrain (0.87 kg/m^2). The active layer TOC estimates in Arctic Alaska were mostly between 20-29 kg/m^2 and therefore higher than the disturbed classes in Ice Creek, but in a similar range to the Shrub Zone (Michaelson et al., 1996). The Northern Circumpolar Soil Carbon Database (Hugelius et al., 2013) summarized all of Herschel Island into one average value of a TOC content of 16.9 kg/m^2 for 0-30cm. This is higher than TOC contents the highest ranking unit (Shrub Zone) for this study with 13.51 kg/m^2 for 0-30cm. Obu et al. (2015) also compared their estimates of TOC content for Herschel Island with the circumpolar database and found that they overestimated TOC (0-100cm) contents by 59%. Obu et al. (2015) suggest overestimations occurred because disturbed mass wasting terrain was not included in the estimates of the circumpolar map because they are not commonly reported in regional TOC studies.

Three approaches, single terrain factors, ecological classes and transects, to describe the spatial distribution of TOC and TN were chosen. Using single terrain features such as slope has the advantage that correlations observed in one study area can easily be compared to other regions. But for the purpose of this project, single terrain features would not be sufficient to fully characterize the spatial and catenary distribution and of TOC and TN within Ice Creek watershed. Ecological classes help distinguishing between types of habitats and give an insight to local soil processes. The same TOC and TN contents can be the result of completely different soil-vegetation interactions and processes. Changes in vegetation community structure are a good indicator for underlying geomorphological slope instabilities (Beylich & Warburton, 2007). Good understanding about local plant ecology is therefore of invaluable help to understand terrain and how it changes through time. Transects taken through different sections of the watershed helped to compare the spatial distribution from the uplands to the stream bed and from source to mouth of the stream. Analyzing soil samples in transects allows for some careful predictions about the directionalities of TOC and TN mobilization, accumulation and losses. However, specific processes of relocation or mineralization of nutrients were not analyzed in the scope of this study.

Terrain

The Spearman correlation analyses of this study suggest that terrain has a large effect on the storage of TOC, TN and CN ratio. The strongest correlations of slope, topsoil moisture, the topographic wetness index (TWI) and the normalized difference vegetation index (NDVI) could be found with CN ratios, closely followed by TOC.

Because TN was generally less strongly correlated, it suggests that terrain has a larger effect on TOC than on TN and that TOC greatly influences the CN ratio. Obu et al. (2015) found no effect of terrain on TN (0-100cm) distribution. In this study, nitrogen values corresponded better with terrain factors for the 0-30cm compared to the entire active layer measurements which could suggest that terrain only has a limited influence on nitrogen contents in the deeper horizons of the soil.

Total nitrogen measurements only give limited information about its actual availability as a nutrient for organisms. Compared to carbon, the geochemical cycling of nitrogen in the soil is much more complex. Moisture and temperature not only influence total nitrogen contents but also rates of ammonification and nitrification (Baumann et al., 2009; Maltby, 2009). Tundra ecosystems are generally nitrogen limited and losses out of the system (atmosphere and water) are expected to be low unless heavily disrupted through permafrost thaw (Frey et al., 2007). Thermal erosion may expose ammonium to aerobic conditions which would enhance nitrification, mineralization and loss of nitrogen (Harms et al., 2014). However, nitrogen availability is highly connected to microbial activity which could counteract these processes. Mooshammer et al. (2014) reported a change in microbial nutrient use efficiency which led to a reduction of nitrogen mineralization (losses) when nitrogen availability was low. Therefore, correlating terrain with TN contents without further analysis of available nitrogen, leaching potential and microbial activity is most likely not capturing all underlying nitrogen dynamics.

CN ratios across the watershed were very low. This is counterintuitive because cold climate are known to slow the decomposition of organic matter which results in large CN ratios and the demobilization of nitrogen (Kuhry & Vitt, 1996). Variation in soil CN ratios across the landscape can be attributed to multiple factors. Plant species have their own typical CN ratio which can still be detected in the decomposing material (Meyer, 1997). Organic matter content in the soil greatly influences the CN ratio such that carbon accumulation (for example because of reducing or cold conditions) heightens the CN ratio (Kuhry & Vitt, 1996). Carbon decomposition through release of CO_2 can also lower CN ratios in the soil (Ping et al., 1998). Because carbon pools in thawing permafrost are highly labile (Vonk et al., 2013), a decrease in CN ratio in newly disturbed areas within the watershed may also be a possibility. However, in this study it is not possible to distinguish whether the substrate origin, organic matter content or recent mineralization are more important drivers in changing CN ratios. An assessment of $\delta^{13}C$ would give more indication about the origin of the sediments (marine, terrestrial) within the area (Meyer, 1997) but it would still be difficult to capture inherent differences within terrestrial vegetation (for example shrubs vs. nitrogen fixating plants) that may influence CN ratios.

Moisture

Of all tested parameters, topsoil moisture showed the highest correlation with TOC, CN and TN-30cm. The strongest relationships could be found with CN ratios. It could be expected that the moisture content is well correlated with high TOC contents (TOC-30cm: ρ =0.74, $p<0.05$, TOC-active ρ =0.61, $p<0.05$). Soil moisture and carbon are linked very tightly: Soil organic matter holds water well and therefore high moisture can be found in the areas with high TOC content (Lantuit et al., 2012). In turn, high moisture content in the soil creates unfavourable conditions of anaerobic respiration and therefore causes the accumulation of carbon (Oechel et al., 1993). In their study on retrogressive thaw slumps on Herschel Island, Lantuit et al. (2012) also noticed a strong linkage between soil moisture and TOC. Conversely, Lawrence et al. (2015) point out that intermediate moisture on the soil surface can trigger a higher turnover of soil carbon and the relationship of moisture and TOC should therefore not be fully linear. It is difficult to separate the effect of moisture from other terrain factors like slope or aspect. Moreover, Lawrence et al. (2015) emphasize that soil moisture can have very localized effect on carbon contents and therefore already small terrain differences can have a great influence on the TOC distribution within the watershed. Arctic studies highlight the close relationship between moisture and other soil properties: Moisture and temperature together are important for the carbon exchange of soil, ground water and atmosphere (Lawrence et al., 2015). According to Pizano et al. (2014), moisture affects plant decomposition and growth. And further, a thick organic layer changes hydrology and temperature control. This suggests that features in the terrain that retain moisture and organic matter enter into a self-accelerating carbon accumulation process. Similar accumulation dynamics can be expected for nitrogen contents. Ammonium forms in moist conditions and renders nitrogen unavailable for plant uptake (Yara, 2015). However, relocations, for example leaching, make it very difficult to account for nitrogen accumulation or removal. CN ratios are usually wide in moist environments, effectively due to organic carbon accumulation (Oechel et al., 1993).

The advantage of the Topographic Wetness Index (TWI) is that it can be detected using RS methods and only requires information about elevation and slope. Yet, the TWI performed much more poorly at describing TOC, TN and CN distribution compared to the field based moisture measurements. Therefore, TWI does not capture the local moisture conditions well enough to be a useful tool for carbon and nitrogen estimates in this study. In their analysis on

TOC and TN distribution across the entire Herschel Island, Obu et al. (2015) found the opposite, TWI corresponded better with TOC and TN than field based moisture measurements. These different findings might be due to the different spatial scales of the studies. Whereas the TWI identifies areas of topographically induced water accumulation it cannot predict where vegetation might hold moisture. Within the Ice Creek watersheds, organic matter and vegetation rich sites may contribute strongly to the topographic effects of moisture accumulation. Other RS methods that could detect moisture are based on Landsat images are because of their coarse resolution (30 m typically) not suitable for this fine scale study. Therefore recent attempts to use radar based systems to accurately predict soil moisture (Wagner et al., 2008) bear a high potential to improve remote sensing based carbon estimates.

Slope

The relationship of TOC, TN and CN to slope was not as strong (ρ between -0.50 and -0.21) but highly significant for TOC and CN. Obu et al. (2015) found slope to be a good predictor for TOC (r^2= -0.68) on Herschel Island. The principal component analysis (PCA) showed that the two ecological zones that were similar in terms of most soil properties (Wet Terrain and Komakuk) divided well on the second PCA axis which is mainly driven by slope. Information on slope is therefore a valuable asset for a deeper understanding of the ecology in the creek. Wet Terrain often forms along the creek and is a site of soil accumulation because it is less steep than the areas above. The frequency of active layer detachments and intensity of solifluction are strongly influenced by slope. Mass wasting, like active layer detachments, very rapidly remove the topsoil and enhance decomposition and carbon degradation and therefore reduce soil organic carbon and nitrogen storage (Pautler et al, 2010; Koven et al., 2011; Pizano et al., 2014). The detached topsoil usually accumulates in the bottom of the slope unless moved by water and mixing of topsoil with lower horizons does not occur (Pizano et. al., 2014). Active layer detachments are therefore important events that shape the watershed. At least just as important are slower, but continuous, processes like solifluction, which is the downward movement of soil destabilized through seasonal frost (Lewkowicz & Harris, 2005). Solifluction usually occurs perpendicular to the valley and is widespread in periglacial environments (Lewkowicz & Harris, 2005; French, 2013). Bare ground on the surface is a sign that erosion is still occurring and that the slope has not been stabilized (Pizano et. al., 2014). However, in this study the PCA gave no insight to a close correlation between bare ground and slope. One reason could be that bare ground also forms through other kind of disturbances like freeze-thaw processes (e.g. mud boils) or fluvial erosion. Most slopes within the watershed are too flat to induce gravity based mass wasting unless melting ice lenses underneath the active layer prompt mass wasting events (Beylich & Warburton, 2007; Bartsch et al., 2009). This makes it more difficult to use slope as a predictor for soil organic carbon and nitrogen.

Normalized Difference Vegetation Index (NDVI)

The NDVI reflects the productivity and density of the vegetation (Burnham & Sletten, 2010). The NDVI and its associated vegetation are a result of terrain properties such as moisture and slope. It is therefore not possible to discuss NDVI as a factor influencing carbon and nitrogen distribution. Instead, this analysis is meant to test the suitability of NDVI as an instrument (and proxy for terrain) to predict TOC, TN or CN ratios within the watershed.

The Circumpolar Arctic Vegetation Map (CAVM) project linked NDVI ranges to specific vegetation types (CAFF, 2015). The PCA in this study showed that the NDVI index captured the extreme ends of the spectrum very well; a high percentage of bare ground was linked to a low NDVI. Values from 0.57 and above are classified as "high biomass and shrubby" according to the CAVM. Most of the NDVI values in this study were in this high range above 0.57 and the question was whether small variations in NDVI would still capture differences in TOC, TN and CN in the soil. Correlations were not as high as with moisture but still highly significant for TOC and CN. The correlation of NDVI with TOC-active in this study (ρ =0.42) was similar to the correlation with TOC (100 cm depth) in a study by Burnham & Sletten (2010) with r^2=0.385. They considered this correlation, albeit small, to be satisfactory because most other surface parameters tested showed even weaker associations.

Suggestions for improvement

Snow depth is greatly influenced by topography and prevailing wind direction. Due to the insulating properties of snow, the depth and melt out has a great effect on the type of vegetation as well as nutrient turnover rates in the soil (Walker et al., 1999). In undisturbed Tundra, under snow banks, nitrogen mineralization is higher (DeMarco et al., 2011; Schimel et al., 2004). The aspect of the slope is the simplest way to estimate areas of high snow accumulation and/or late melt out times. Aspect was however not considered in this study because of the lack of control information on snow cover. Burnham & Sletten (2010) found aspect to improve their predictions. Due to the importance of snow cover on soil properties, more effort will be put into investigating the distribution of snow on Herschel Island in the coming years.

Only the soil moisture content of the first 20 cm was analyzed in this study. This may explain the lower correspondence of TOC, TN and CN ratios for the entire active layer depth. Active layer depth varied for each soil profile and higher variations in nutrient content for the entire active layer depth may therefore be linked to this variability.

During field work, no separate organic horizon sample was taken. Therefore, the uppermost sample was a mixture of organic (if deep enough) and mineral horizons and skewed depending on the thickness of the organic horizon. Due to their greatly different properties such as density and water retention capacity, a separate organic horizon sample would have been necessary to fully understand how moisture and slope affect the soil surface (Fuchs et al., 2015).

Ecological Class Approach

The spatial distribution of ecological classes within the Ice Creek (IC) watersheds reflects the patterns that can be seen on Herschel Island as a whole. In general, the carbon rich Herschel areas were found in the flat upland terrain of the watershed. Decomposition rates of the typically occurring *Eriophorum. vaginatum*, sedges and S*alix pulchra* are slow in this environment and CN ratios are therefore large (Smith et al., 1989). The Ice Creek West contained greater areas of the Herschel class than Ice Creek East and therefore had more terrain unaffected by erosion. The higher percentage of Herschel in IC West did however not notably increase total carbon storage within the watershed.

The Komakuk areas almost formed a belt around the Herschel terrain. The terrain was slightly steeper and the vegetation changed from tussock forming plants to a rather slow lying vegetation cover of *Dryas integrifolia*, *Salix arctica* and *Salix reticulata*. According to Smith et al. (1989), it is too simplistic to assume that Komakuk occurs in sites where there is too much disturbance for Herschel vegetation to grow. Komakuk consists of a very stable vegetation community that not necessarily experiences much disturbance but due to its catenary position does not accumulate as much organic matter and therefore creates different growing conditions. A quicker turnover of nutrients was reflected in a lower CN ratio. Despite its lower carbon content, nitrogen quantities did not differ, which is a sign that the soil is well aerated and mineralization occurs (Harms et al., 2014). Komakuk was a common ecological unit in both watersheds but occurred more frequently in IC East. Erosion of topsoil from these areas would contribute to less carbon loss than Herschel terrain but the active layer depth in Komakuk was usually deeper, which could contribute to expose more soil to subsurface flows (Harms et al., 2014). The area identified as Herschel-Komakuk (HK) displayed characteristics of both Herschel and Komakuk (Sedges and *Salix arctica*).

The Plover-Jaeger (PJ) units were mostly found in the area where Ice Creek East and West are joining in the lowest section of the watershed. It is an area that has most likely been highly affected by thermal erosion. The other area that was dominated by the Plover-Jaeger unit was in the upper section of Ice Creek West. These areas were characterized by deep incisions and thermal erosion gullies. Low CN ratios may give the false impression that productivity would be high. The high percentage of nitrogen fixing plants indicates that the PJ areas are nitrogen deficient. Harms et al. (2004) suggest that nitrogen fixating plants mask some of the nitrogen deficiency in the soil. But no further analysis on the composition of the nitrogen was done in this study. These analyses could help to indicate how high the contribution of nitrogen fixating plants is.

Thrasher only occurred in very localized patches. Commonly, those areas were on steep slopes that had formed during recent thermal erosion, on flat soil accumulation terrain or in the form of mud boils. Steep sites may have stayed vegetation free for longer times. Accumulation sites, however, can quickly get recolonized by vegetation. In the Ice Creek watershed, some *Artemesia* species, grasses and chamomile were the first colonizers. Quick recolonization by plants makes it difficult to recognize high disturbance areas through satellite imagery.

The above discussed ecological classes have been defined by Smith et al. (1989). The Wet Terrain and Shrub Zone were added during the field season in 2014 because some areas could not be characterized by the existing ecological classes. There has been a significant increase in tall erect shrubs within the past decades across Herschel Island which required adding them as a group to fully characterize the ecology (Myers-Smith et al., 2011). Wet Terrain is a prominent feature of Ice Creek catchment and is existent across the island. It forms in sites that frequently get flooded or were water seeps out from the slopes.

In terms of TOC and TN content, the Shrub Zone was comparable to Herschel terrain. This, however, does not imply that soil dynamics are similar. On eroded and disturbed terrain, plant communities often do not go back to their original state but new communities form (Lantuit et al., 2012). In recent decades, disturbance sites in the low Arctic have seen a high percentage of shrub regrowth (Myers-Smith et al., 2011). Shrubs have thick long roots and may therefore increase nutrient exchange from and to lower horizons of the active layer. Whereas, Herschel was usually found on flat terrain, the Shrub Zone was mostly found on intermediate slopes in the lower part of the watershed. Therefore, Shrub Zone areas can be affected by solifluction and downward creep of soil, which leads to carbon relocation into and out of these sites. Because Shrub Zones are a relatively new phenomenon on Herschel Island, there are no available information on the relative magnitude of accumulation and relocation. Because it is occupying the highest elevations in the watershed, Herschel obtains its moisture only from direct inputs, through rainfall. Shrub Zones were found closer towards the bottom of the watershed and therefore receive not only direct rainwater but also surface and subsurface flow. Furthermore, late melting snow banks may feed water until mid-summer. A change in rainfall patterns, snow melt-out times and erosion rates may therefore affect Herschel and Shrub Zones differently.

The Wet Terrain is a distinctive land feature due to a high percentage of bright green *Equisetum arvense* and *Petasites frigidus*. Both species can tolerate high soil moisture and can sustain regular flooding. The Wet Terrain occurred on the gentle slopes in the upper reach of the watershed and along creeks. The Wet Terrain sampling locations in proximity to the stream were characterized by a very deep active layer (in 2015, often deeper than one meter) most likely as a result of sediment accumulation. Disturbances were frequent enough to restrict stratification of the soil (see soil sample properties in the Appendix). The disturbances in the Wet Terrain unit are different from other areas within the Ice Creek. A deep active layer depths suggest that common slope processes are probably more important than cold environment specific one like cryoturbation. New material gets accumulated either through erosion or fluvial deposits, burying older sediments and locking them away from aerobic conditions; this can lead to carbon and nitrogen sequestration. Within this ecological class, there was a strong positive correlation of topsoil moisture and CN ratios. Recently disturbed sites like Wet Terrain should be subject to quick mineralization (Vonk et al., 2013) but it is could be slowed down due to high soil moisture contents.

Transect Based Approach

Three cross sectional transects were taken through the valley. They were placed in the upper, middle and lower reach of the watershed, although the upper transect only passed through Ice Creek West. Exact transect locations can be obtained from figure 10 in the Methods. Total organic carbon values were presented as histograms along transects at each sampling location. Additionally, averages of TOC, TN and CN were compared between transects.

Figure 21 shows soil TOC content across all three transects. In the upper transect of Ice Creek, the channel had not created a deep incision and slopes toward the creek were not steep. TOC contents in the soil were very similar between locations. This suggests that terrain was an important factor for TOC distribution. Similar contents of TOC-30cm and TOC-active can mainly be attributed to shallow active layer depths which often did not reach much further than 30 cm. Toward the mouth of the creek, the incision into the valley was much deeper and TOC contents along the transects varied strongly between locations.

The undisturbed areas on the far west and east of the transects had similar characteristics to the sampling locations further upstream, TOC contents were high but active layer depths were shallow so that most carbon was stored in the first 30 cm. TOC contents did not decrease linearly towards the stream and the proportion of carbon stored below 30 cm varied greatly. Areas with low carbon content were often followed by accumulation sites toward the creek. Most notable was the high percentage of below 30 cm carbon in those accumulation sites. Isotope analysis of ^{14}C could give more information about the origin and age of the carbon found in the accumulation sites (Beylich & Warburton, 2007). Sediment accumulation could have occurred recently during mass wasting processes. Or, alternatively, through slow long term processes that started after the last ice age where vegetation cover was still minimal (H. Lantuit, personal communication). The current distribution of carbon suggests that nutrients lost at one location do not necessarily leave the watershed but merely get redistributed. No information is available of the biochemical stability of the organic components in sediment at these accumulation sites in the Ice Creek watershed. Therefore, at this stage, it is not possible to say how much of the carbon and nitrogen get mineralized or lost to the atmosphere. Carbon accumulation could be attributed to at least three different major factors: slope, moisture and vegetation. Flat terrain may act as a sediment trap and therefore prevent soil, including organic material from relocating further downslope. Fresh disturbances are likely to enhance mineralization rates of carbon and nitrogen (Vonk et al., 2013) but because soil moisture is also high in these localized depressions, this might slow down mineralization processes and thus lead to the accumulation of carbon (Oechel et al., 1993). Alternatively, dense shrub vegetation also has the capacity to prevent sediments from moving further downslope. Shrub areas are not necessarily very moist and carbon accumulation might therefore be a recent process and due to slowly decomposing woody material. Obu et al. (2015) found some of the largest variations in soil carbon content in accumulation sites. This suggests that multiple processes have an effect on the magnitude of carbon storage at these locations. Further research should try to quantify accumulation, mineralization and remobilization processes in these deposition zones.

High soil carbon content in the middle ridge between Ice Creek West and East can mainly be attributed to an old peat lens found in one of the sampling sites. The two sampling location East of the middle ridge also had some of the highest TOC-active values. This suggests that in this section of the watershed there are still large amounts of organic carbon stored in the soil which has been preserved from mineralization so far. A dense transect along this ridge that further investigates solifluction, cryoturbation intensity and age would be necessary to estimate the proportion of old organic carbon that has been buried thousands of years ago and movements that could be attributed to more recent disturbances. Following that same ridge towards the confluence of Ice Creek East and West, carbon contents decreased noticeably. The ridge is south exposed and a mixture of permafrost thaw and fluvial erosion most likely have destabilized the tip of the ridge.

In comparison, the IC East sampling locations showed less accumulation sites. Uplands soils with high carbon contents measured were followed by samples with some of the lowest carbon contents found within the watershed (see figure 21, transect *middle* and *lower* on the far right).

The boxplots (figure 22) showed a similar trend for both TOC and TN contents. Values were higher in the upper reach and lower in the bottom of the watershed. This trend was more pronounced for the first 30 cm of the soil than the entire depth of the active layer (not shown). Variation around the median in the middle and lower transects were very high. Selection of sampling locations, even if they were taken as representative as possible, can have a great influence on the average values of TOC and TN contents in the transects. The downward trend of TOC and TN toward the bottom of the watershed can be attributed to highly disturbed, barren sampling locations that were not present in the upper reach. The upper reach of the watershed contains a far higher proportion of densely vegetated upland areas. To ensure a better comparability between transects, for a second analysis, only sampling locations directly adjacent to the stream were selected. The comparison of CN ratios just along the creek should remove some of the terrain bias and gives better information about organic matter and sediment transport. CN ratios were highest close to the creek in the upper transect and decreased towards the bottom of the watershed. According to S. Lamoureux (personal communication), the most likely explanation for this trend is that in the upper watershed material that got accumulated close to the stream is rich in organic matter, which inherently has a large CN ratio. In the lower reaches of the watershed, sediments poor in organic matter were relocated and deposited by the stream. The lack of organic matter (rich in stable organic carbon) resulted in a narrow CN ratio. Furthermore, highly disturbed sites might already eroded deep sediments that are of marine origin and naturally have lower CN ratios (Meyers, 1997). In small creeks, relocation of material through the water channel is thought to be minimal (Lamoureux & Lafrenière, 2014). Therefore, erosion sites are likely found in proximity to accumulation areas. Sediments found in the lower reach of Ice Creek are relocated from disturbance sites on stream adjacent slopes. However, sediment loads in small arctic streams like Ice Creek vary considerably throughout the year. Seasonal peaks of high flow and high suspended material concentrations can be observed during snow melt (Cockburn & Lamoureux, 2008). This implies that relocation from the upper reach of the watershed should happen, even if only seasonally. Upstream material that gets relocated during those flooding events in Ice Creek either got masked by the higher proportion of local sediments in the lower reach, implying that CN ratios could be even lower if it was not for upstream sources. Or, alternatively, suspended materials got transported all the way to the floodplain or ocean.

5.3 Ice Creek Watershed and Climate Change

It is thought that a warming climate will turn Cryosols from carbon sinks into carbon sources (Schuur et al., 2015). More carbon that is released to the atmosphere will enhance further warming and therefore lead to self-accelerating feedback loop (Schuur et al., 2015). It would be too simplistic to assume that climate in North West Canada would solely get warmer. Researchers from many different fields of study agree that seasonality, and especially for cold environments, that the state of the precipitation (rain vs. snow) are of great importance (Cooper, 2014). Of all possible changes, extreme events such as intensive summer rainfall and an early melt out of snow coupled with long warm summers are some of the most likely to occur (Lamoureux et al., 2014). All landscape changes have the potential to induce irreversible shifts in the hydrology of the watershed (Beylich & Warburton, 2007). Because sediment fluxes are determined by both regular processes and irregular or periodic events, a changing climate could affect these long and short term fluxes differently.

Mass wasting is one of the events that occur with spatial and temporal irregularity (Lewkowicz & Harris, 2005). Burnham & Sletten (2010) and Lantuit et al. (2012) among others predict that with longer and warmer summers more active layer detachments will be observed because melting ground ice reduces the shear strength of slopes. Similarly, Lewkowicz & Harris (2005) observed that active layer detachments increase in frequency and magnitude in very hot periods if coupled with heavy rainstorms. Heavy rainstorms alone can effectively also trigger slope failure and mudflows and are not necessarily related to the cryological properties of the soil (Beylich & Warburton, 2007).

Besides mass wasting, slower but continuous changes can alter the sediment and nutrient fluxes within the watershed. Deeper thawing will remobilize nutrients that have been conserved by the cold (Hugelius et al., 2014, Fuchs et al., 2015). Oechel (1989) analyzed nutrient flows in a small Arctic watershed and found nutrients to move 10 meters downslope which is faster than possible solifluction or downcreep of soil (Bartsch et al., 2009). The above described mechanism indicates that climate change can induce terrain changes. Even small terrain changes can alter the moisture regime of a landscape and effectively also change the dynamics of CO_2 and CH_4 emissions to the atmosphere (Natali et al., 2015).

Climate change therefore has the potential to alter carbon and nitrogen fluxes within the Ice Creek watershed. For watershed based studies, the sediment budget equation can help to understand possible soil movements. A sediment budget is "an accounting of the sources and disposition of sediment as it travels from its point of origin to its eventual exit from a drainage basin" (Reid & Dunne, 1996, p. 3). Sediment budget studies follow this basic equation:

$$I=O+\Delta S$$

I = *inputs*
O = *outputs*
ΔS = *change in net storage of sediments*

The equation is a useful tool to identify areas of mobilization, accumulation and loss within the watershed. This study, however, is focussing on spatial distribution of total organic carbon (TOC) and nitrogen (TN) in the soil. The sediment budget equation does not capture all possible pathways carbon and nutrients (organic matter) could take. Other pathways include atmospheric exchange for instance; this can alter both the input and the output variables. Organic matter accumulation can increase the possible TOC and TN inputs to the catchment. And, the *output* variable should be divided into fluvial and atmospheric outputs to also account for carbon and nitrogen mineralization.

Areas that are currently inactive in terms of carbon release may become part of a semi active zone which experiences periodic disturbances. For example, the upland Herschel areas that are currently not contributing much to the inputs may be destabilized through retrogressive thaw slumping. In the Komakuk zone, deepening of the active layer could increase solifluction and formation of new thermal erosion channels. Because carbon storage is often high in these areas, even smaller erosion events can release significant amounts of carbon that had been stored for centuries. Lamoureux & Lafrenière (2014) found that recent disturbances were releasing very old particulate organic carbon. If the intensity of mass wasting events increases more sediments and material might enter the accumulation sites close to the creek. Soil and nutrient accumulation areas in proximity to the creek may leave the system through fluvial erosion and become part of the output. Which of these processes (accumulation or outwash) is more dominant will determine if there is a net increase in nutrient output or storage. Poles (measuring sticks) installed at accumulation sites could give a rough estimate if storage decreases or which flooding events are strong enough to significantly erode older accumulation areas (Beylich & Warburton, 2007). If an increase in disturbances and climate change further promotes tall shrub expansion, vegetation could over impose terrain effects on carbon and nitrogen storage (Beylich & Warburton, 2007; Myers-Smith et al., 2014). Deep shrub roots have an influence on slope stability, woody debris is slow at decomposing and the structure of the above soil vegetation might act as a barrier to sediment movements (Durán Zuazo & Rodríguez Pleguezuelo, 2008). Therefore, emerging shrub zones have the potential to increase the carbon and nitrogen storage potential. The Herschel upland is poorly drained because tussock forming *Eriophorum vaginatum* and *Carex* species and their debris hold the moisture and active layer depths are shallow. Warm and dry summers can result in drying of these uplands, which enhances mineralization of organic matter, leading to a net loss of carbon and nitrogen (Oechel et al., 1993). Permafrost thaw will affect areas with shallow active layer depth the most because the transitional zone usually still holds large quantities of carbon as a relic from warmer periods in past centuries (Bockheim, 2015; Obu et al., 2015). Although the general direction of potential soil processes and sediment fluxes for the Ice Creek watershed can be identified, its quantification has been lacking so far. Different projects currently investigate moisture regimes, carbon release potential and hydrology of the watershed. An in depth analysis of atmospheric release and the importance of vegetation for terrain stability are nevertheless still lacking. Long term analyses are needed to capture changes in sediment fluxes over time (Braun et al., 2000). Furthermore, it is important that these studies integrate both contemporary and historic time scales to correctly estimate the effects of climate change (Beylich et al., 2005). Analyses from already existing experimental watersheds in cold environments are a good baseline to understand the main driving forces behind carbon and nitrogen dynamics (Lamoureux & Lafrenière, 2014, Lamoureux et al., 2014; Bartsch et al., 2009). However, better estimates, from a greater diversity of landscape types are needed to estimate the impact small Arctic watersheds have on carbon release and climate change. Projects like Sediflux: Sedimentary Source-to-Sink-Fluxes in Cold Environments (Beylich & Warburton, 2007) and a recent call for workshop participants for “Advancing Integrated, Cross-cutting Practices for Arctic Flux Observations in Terrestrial Environments” (IASOA, 20015) highlight the importance of more in depth and comparable studies on nutrient fluxes in cold environments.

6. Conclusion

The active layer of Ice Creek watershed contains 33391 tonnes of TOC and 3635 tonnes of TN which is lower than the average value reported for Herschel Island by the Northern Circumpolar Soil Carbon Database. It is, however, comparable to values reported elsewhere in the Arctic. The difference with the Northern Circumpolar Soil Carbon Database can mainly be attributed to the inclusion of disturbed sampling locations with little to no vegetation cover and low organic matter content in this study. There was no striking difference in TOC and TN storage between Ice Creek East and West.

The detectability of Herschel specific ecological classes was not fully satisfactory but not worse than vegetation classes that are based on indicator species. More ground truthing points would be needed to validate these results. Unless a better classification system is found, it is recommended to continue to use the ecological class approach but create a key to help with identifying ecological classes in the field. Although variance of CN, TOC and TN values within classes was large at times, other arctic remote sensing research projects reported even higher in class variation and overlap. Single factors like slope could be utilized to explain within class variance to further optimize of CN, TOC or TN predictions.

Topsoil moisture was the best predictor for soil organic carbon and nitrogen. A low correlation with the topographic wetness index (TWI) and carbon suggests that soil moisture is highly influenced by vegetation growth. Given the high correlation of soil moisture with carbon and nitrogen content, this thesis should encourage further research to integrate satellite radar moisture information with field data to improve mapping. High carbon contents were mainly found on flat terrain and low contents on steep terrain but slope alone was not a good enough predictor for TOC.

The normalized difference vegetation index (NDVI) explained approximately 50% of the TOC distribution which is, compared to other studies, relatively high. As long as soil moisture estimates via RS systems are not fully developed this is currently the single factor to best predict soil organic carbon. Snow depth measurements could also greatly contribute to improve TOC and TN estimates.

Flat upland (Herschel) terrain and tall erect bush areas (Shrub Zone) contained the largest amount TOC and TN. The lowest contents could be found in the steep and frequently eroded zones (Thrasher and Plover-Jaeger). High carbon accumulation along the stream banks and higher CN ratios in the upper reach suggests that fluvial processes do not remove all the eroded sediments from the watershed.

An intensification of summer rainfall and warmer temperatures would alter the hydrological patterns of the watershed and current accumulation sites may release more carbon toward the Beaufort Sea. In addition to the planned hydrological assessments, detailed studies that focus specifically on sediment remobilization and atmospheric losses of carbon are crucial to understand the role small watersheds play in the face of a changing climate.

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Appendix

Soil sample properties

Sample	Depth (cm)	Conduc Tivity (uS)	pH	water content %	dry bulk density	N%	C%	TOC%	TIC%	ρOC (g/cm3)	ρTN (g/cm3)	CN	SOC storage (kg/m2)	TN storage (kg/m2)	coarse fragment (%)
ICE-HE-14-12-1	5-11	255.0	7.26	60.6	0.40	0.78	11.45	10.69	0.76	0.042	0.0031	13.78	5.50	0.40	4.7
ICE-HE-14-12-2	15-21	145.3	6.94	43.0	0.76	0.48	6.86	5.90	0.96	0.045	0.0036	12.38	5.18	0.42	5.3
ICE-HE-14-12-3	28-36	116.2	7.02	34.2	1.04	0.31	4.19	3.58	0.61	0.037	0.0032	11.55	4.28	0.37	0.0
ICE-HK-14-11-1	5-11	174.2	7.18	26.9	1.07	0.23	2.91	2.55	0.36	0.027	0.0024	11.27	3.54	0.31	0.0
ICE-HK-14-11-2	15-21	163.5	6.98	26.4	1.15	0.22	2.62	2.21	0.41	0.025	0.0025	10.17	4.71	0.46	0.1
ICE-HK-14-11-3	42-48	395.0	7.64	53.0	0.59	1.12	18.14	16.67	1.47	0.098	0.0066	14.85	16.12	1.09	0.0
ICE-JT-14-15-1	5-11	35.9	7.88	23.0	1.30	0.11	1.89	0.69	1.20	0.009	0.0015	6.00	1.16	0.19	0.0
ICE-JT-14-15-2	15-21	15.7	8.20	22.8	1.35	0.11	2.01	0.57	1.44	0.008	0.0015	5.20	2.46	0.47	-1.5
ICE-JT-14-15-3	69-75	14.6	8.13	25.8	1.25	0.10	2.23	0.53	1.70	0.007	0.0013	5.08	1.99	0.39	16.7
ICE-KO-14-1-1	8-14	1170.0	8.09	33.7	0.99	0.34	4.87	4.01	0.86	0.040	0.0034	11.64	7.76	0.67	0.0
ICE-KO-14-1-2	25-31	-	-	31.2	0.93	0.27	3.73	2.79	0.94	0.026	0.0025	10.24	3.52	0.34	0.0
ICE-KO-14-1-3	35-41	1359.0	7.87	40.7	0.78	0.47	7.00	5.67	1.33	0.044	0.0037	11.94	5.05	0.42	2.7
ICE-KO-14-1-4	48-54	4.3	7.77	24.3	1.41	0.17	3.02	1.31	1.71	0.018	0.0024	7.75	1.75	0.23	0.0
ICE-KO-14-7-1	5-11	502.0	7.82	60.8	0.42	1.13	15.67	14.29	1.38	0.061	0.0048	12.69	7.89	0.62	4.6
ICE-KO-14-7-2	15-21	677.0	8.08	22.9	1.29	0.19	2.77	1.55	1.22	0.020	0.0025	8.00	3.90	0.49	0.0
ICE-KO-14-7-3	44-50	947.0	8.10	23.0	1.39	0.16	2.20	0.94	1.26	0.013	0.0023	5.77	2.30	0.40	1.0
ICE-PJ-14-13-1	5-11	-	-	11.2	1.21	0.07	1.67	0.41	1.26	0.005	0.0009	5.59	0.65	0.12	27.0
ICE-PJ-14-13-2	15-21	-	-	9.6	1.40	0.06	1.74	0.15	1.59	0.002	0.0008	2.57	0.62	0.24	41.5
ICE-PJ-14-13-3	66-72	-	-	3.9	1.69	0.02	1.30	0.05	1.25	0.001	0.0004	2.36	0.24	0.10	85.4
ICE-PJ-14-8-1	5-11	-	-	4.4	1.32	0.05	1.52	0.55	0.98	0.007	0.0007	10.82	0.93	0.09	81.8
ICE-PJ-14-8-2	15-21	-	-	5.1	1.42	0.03	1.04	0.05	0.99	0.001	0.0004	1.76	0.23	0.13	73.7
ICE-PJ-14-8-3	70-76	-	-	5.2	1.61	0.01	1.61	0.05	1.56	0.001	0.0001	6.21	0.25	0.04	88.5
ICE-SZ-14-10-1	5-11	609.0	7.47	63.1	0.35	0.91	13.44	12.67	0.76	0.044	0.0032	13.88	5.73	0.41	2.3
ICE-SZ-14-10-2	15-21	346.0	7.36	57.8	0.51	0.80	11.09	10.23	0.87	0.052	0.0041	12.82	6.53	0.51	0.0
ICE-SZ-14-10-3	30-36	331.0	7.66	28.3	1.09	0.27	3.07	2.58	0.49	0.028	0.0030	9.48	5.51	0.58	0.0
ICE-SZ-14-10-4	54-60	-	-	25.7	1.20	0.21	2.80	1.85	0.95	0.022	0.0025	8.81	3.33	0.38	0.0
ICE-TZ-14-14-1	5-11	2.2	8.00	27.7	1.11	0.21	2.99	1.74	1.24	0.019	0.0024	8.16	2.51	0.31	16.1
ICE-TZ-14-14-2	15-21	-	-	21.5	1.16	0.15	2.24	0.92	1.32	0.011	0.0017	6.14	2.63	0.43	6.3
ICE-TZ-14-14-3	54-60	-	-	24.3	1.37	0.11	1.74	0.52	1.22	0.007	0.0015	4.66	1.59	0.34	10.3
ICE-TZ-14-2-1	12-18	686.0	7.52	47.7	0.69	0.60	7.78	7.26	0.52	0.050	0.0042	12.12	9.81	0.81	0.0
ICE-TZ-14-2-2	21-27	847.0	7.83	21.4	1.41	0.18	2.36	1.57	0.79	0.022	0.0025	8.81	2.76	0.31	0.5
ICE-TZ-14-2-3	37-43	866.0	7.94	21.7	1.41	0.21	2.54	1.89	0.65	0.027	0.0030	8.93	2.93	0.33	0.0
ICE-TZ-14-9-1	5-11	373.0	7.06	56.9	0.51	0.67	8.84	7.96	0.89	0.041	0.0035	11.80	5.32	0.45	8.8
ICE-TZ-14-9-2	15-21	202.0	7.11	51.0	0.65	0.69	8.74	7.87	0.86	0.051	0.0045	11.46	6.14	0.54	4.0
ICE-TZ-14-9-3	29-35	211.0	7.12	45.4	0.77	0.62	7.31	6.42	0.89	0.049	0.0047	10.37	4.92	0.47	1.5

Sample	Depth (cm)	Conduc tivity (uS)	pH	water content %	dry bulk density	N%	C%	TOC%	TIC%	ρOC (g/cm3)	ρTN (g/cm3)	CN	SOC storage (kg/m2)	TN storage (kg/m2)	coarse fragments (%)
ICW-HE-14-1-1	5-11	90.5	6.86	27.9	1.03	0.23	3.62	3.11	0.51	0.032	0.0024	13.50	4.95	0.37	0.0
ICW-HE-14-1-2	20-26	157.2	7.11	27.8	1.27	0.24	3.59	3.02	0.57	0.038	0.0030	12.60	4.77	0.38	0.0
ICW-HE-14-1-3	30-36	240.0	7.01	26.9	1.13	0.29	4.61	3.73	0.88	0.042	0.0033	12.98	3.38	0.26	0.0
ICW-HE-14-8-1	5-11	339.0	7.16	81.3	0.14	1.43	33.59	32.25	1.34	0.044	0.0019	22.55	5.69	0.25	17.2
ICW-HE-14-8-2	15-21	-	-	32.6	1.07	0.26	3.80	3.29	0.51	0.035	0.0028	12.78	3.88	0.30	0.0
ICW-HE-14-8-3	27-33	136.9	6.30	46.6	0.68	0.58	8.40	6.76	1.65	0.046	0.0040	11.67	4.16	0.36	0.8
ICW-KO-14-14-1	5-11	907.0	7.91	46.9	0.40	0.56	8.78	7.37	1.41	0.030	0.0023	13.20	3.86	0.29	14.2
ICW-KO-14-14-2	15-21	581.0	8.15	24.8	1.06	0.20	3.19	1.62	1.57	0.017	0.0021	8.17	3.78	0.46	10.1
ICW-KO-14-14-3	49-55	672.0	8.02	24.5	1.20	0.16	2.61	1.18	1.44	0.014	0.0019	7.27	2.82	0.39	0.0
ICW-KO-14-5-1	5-11	775.0	8.20	22.3	1.04	0.21	3.48	1.83	1.64	0.019	0.0021	8.92	2.47	0.28	6.8
ICW-KO-14-5-2	15-21	-	-	20.8	1.29	0.16	2.84	1.13	1.72	0.015	0.0020	7.11	3.71	0.52	1.5
ICW-KO-14-5-3	56-62	806.0	7.99	22.7	1.38	0.14	2.93	0.88	2.06	0.012	0.0019	6.32	2.84	0.45	1.6
ICW-PJ-14-10-1	9-15	306.0	7.90	13.6	1.57	0.48	6.17	5.08	1.09	0.080	0.0075	10.69	14.37	1.34	67.3
ICW-PJ-14-10-2	21-27	380.0	7.96	21.0	1.24	0.08	3.28	0.69	2.59	0.009	0.0009	9.20	1.29	0.14	15.6
ICW-PJ-14-10-3	39-45	206.0	8.03	17.2	1.40	0.01	2.53	0.05	2.48	0.001	0.0001	6.59	0.17	0.03	0.0
ICW-PJ-14-10-4	69-75	1208.0	7.95	21.5	1.35	0.02	3.11	0.05	3.06	0.001	0.0003	2.43	0.12	0.05	0.0
ICW-PJ-14-11-1	5-11	781.0	8.24	22.2	1.40	0.15	2.35	0.79	1.56	0.011	0.0021	5.23	1.44	0.28	3.1
ICW-PJ-14-11-2	15-21	760.0	8.36	24.7	1.30	0.14	2.04	0.64	1.40	0.008	0.0018	4.63	2.47	0.53	2.2
ICW-PJ-14-11-3	64-70	2.0	8.14	20.9	1.40	0.15	2.07	0.74	1.33	0.010	0.0020	5.12	2.88	0.56	4.1
ICW-SZ-14-15-1	5-11	497.0	7.42	62.7	0.37	0.97	14.77	13.38	1.39	0.049	0.0036	13.80	6.39	0.46	20.6
ICW-SZ-14-15-2	15-21	586.0	8.19	48.1	0.68	0.56	7.18	6.24	0.93	0.042	0.0038	11.23	9.77	0.87	3.6
ICW-SZ-14-15-3	51-57	765.0	7.83	30.2	1.08	0.25	3.61	2.81	0.80	0.030	0.0027	11.23	6.40	0.57	5.9
ICW-TH-14-12-1	5-11	-	-	3.9	1.54	0.04	1.52	0.19	1.33	0.003	0.0007	4.51	0.46	0.10	87.8
ICW-TH-14-12-2	20-26	-	-	3.6	1.44	0.02	1.09	0.05	1.04	0.001	0.0003	2.33	0.20	0.09	80.9
ICW-TH-14-12-3	60-66	361.0	8.18	12.6	1.36	0.05	1.96	0.18	1.78	0.002	0.0007	3.61	0.56	0.15	24.1
ICW-TH-14-9-1	5-11	-	-	19.8	1.22	0.15	2.29	0.84	1.45	0.010	0.0019	5.48	1.33	0.24	1.7
ICW-TH-14-9-2	15-21	8.3	8.00	22.6	1.39	0.13	2.07	0.67	1.40	0.009	0.0019	4.94	3.19	0.64	1.2
ICW-TH-14-9-3	74-80	-	-	28.2	1.16	0.13	1.93	0.76	1.17	0.009	0.0016	5.67	2.87	0.51	5.5
ICW-TZ-14-13-1	5-11	695.0	7.93	44.5	0.59	0.53	7.05	5.65	1.40	0.033	0.0031	10.62	4.31	0.41	2.8
ICW-TZ-14-13-2	15-21	796.0	8.25	29.7	0.95	0.21	3.42	2.21	1.20	0.021	0.0020	10.53	3.56	0.34	0.3
ICW-TZ-14-13-3	39-45	703.0	7.91	38.4	0.90	0.35	4.74	3.88	0.86	0.035	0.0032	11.02	5.23	0.47	1.5
ICW-TZ-14-2-1	7-12	434.0	7.84	31.4	0.97	0.37	4.64	3.81	0.82	0.037	0.0036	10.33	4.80	0.46	25.5
ICW-TZ-14-2-2	14-19	422.0	7.75	31.5	1.04	0.30	3.80	3.28	0.52	0.034	0.0031	11.03	2.56	0.23	2.9
ICW-TZ-14-2-3	22-28	740.0	8.03	32.0	0.91	0.32	3.95	3.42	0.53	0.031	0.0029	10.56	3.41	0.32	0.0
ICW-TZ-14-2-4	35-40	1124.0	8.01	18.7	1.34	0.11	1.87	0.43	1.43	0.006	0.0015	3.98	0.49	0.12	36.5
ICW-TZ-14-6-1	5-11	-	-	21.1	1.27	0.22	3.07	1.88	1.19	0.024	0.0028	8.54	3.09	0.36	8.6
ICW-TZ-14-6-2	15-21	836.0	7.94	23.2	1.34	0.20	2.69	1.56	1.13	0.021	0.0027	7.77	6.69	0.86	2.9
ICW-TZ-14-6-3	69-75	1057.0	7.85	25.7	1.25	0.20	2.67	1.66	1.00	0.021	0.0025	8.41	6.23	0.74	22.4

Location properties

Part1

ID	stream section	Eco class	Vege tation name	Spec. rich ness	depth (cm)	Depth organic	moisture	Bulk density	Grain coarse	SOC 30cm	SOC active	TN 30cm	TN active	CN 30	CN active	Bare ground %	litter %	distance stream (m)
ICE-HE-14-12	Lower	HE	Erioph orum	20	36	9	60.6	0.40	4.68	12.72	14.95	1.00	1.19	12.74	12.54	0	66.5	234.8
ICE-HK-14-11	Middle	HK	Erioph orum	19	48	5	26.9	1.07	0.00	7.85	24.71	0.74	1.88	10.60	13.12	0.75	77	301.6
ICE-JT-14-15	Lower	PJ	Camo mille	6	75	0	23	1.30	0.00	2.45	5.59	0.44	1.06	5.52	5.29	192.5	53	176.7
ICE-KO-14-01	Upper	KO	Dryas	10	41	5	33.7	0.99	0.00	10.43	18.07	0.93	1.66	11.22	10.88	1.4	67.5	118.4
ICE-KO-14-07	Middle	KO	Dryas	15	50	5	60.8	0.42	4.64	10.89	13.65	1.02	1.48	10.63	9.20	0	38	124.0
ICE-PJ-14-08	Middle	PJ	Salix-Lupine	18	76	2	4.4	1.32	81.84	0.99	1.35	0.15	0.25	6.51	5.32	38	46	48.7
ICE-PJ-14-13	Lower	PJ	Salix-Lupine	16	72	2	11.2	1.21	27.04	0.96	1.47	0.25	0.46	3.86	3.23	74	61.5	61.1
ICE-SZ-14-10	Middle	SZ	Shrub	20	60	8	63.1	0.35	2.33	13.49	20.99	1.06	1.88	12.73	11.17	0	78.5	7.2
ICE-TZ-14-02	Upper	WT	Petasites	12	43	10	47.7	0.69	0.00	11.99	15.41	1.06	1.45	11.26	10.64	0.2	48.5	19.8
ICE-TZ-14-09	Middle	WT	Petasites	14	35	10	56.9	0.51	8.81	14.00	16.46	1.24	1.47	11.32	11.17	5.75	55	29.5
ICE-TZ-14-14	Lower	WT	Petasites	16	60	2	27.7	1.11	16.06	4.25	6.63	0.60	1.07	7.10	6.19	0	88.5	24.2
ICW-HE-14-01	Upper	HE	Erioph orum	11	36	4	27.9	1.03	0.00	10.64	13.17	0.82	1.01	13.04	13.03	0	48.25	140.0
ICW-HE-14-08	Middle	HE	Erioph orum	21	33	13	81.3	0.14	17.23	12.37	13.76	0.81	0.93	15.20	14.75	0	52	153.9
ICW-KO-14-05	Middle	KO	Dryas	13	62	5	22.3	1.04	6.79	4.90	8.97	0.62	1.25	7.85	7.19	0	76	146.0
ICW-KO-14-14	Lower	KO	Dryas	10	55	12	46.9	0.40	14.21	6.65	10.31	0.65	1.14	10.26	9.04	0	87.5	162.3
ICW-PJ-14-10	Upper	PJ	Salix-Lupine	17	75	2	13.6	1.57	67.30	14.69	15.16	1.39	1.49	10.56	10.18	16.5	61	81.6
ICW-PJ-14-11	Lower	PJ	Salix-Lupine	17	70	2	22.2	1.40	3.14	2.83	6.77	0.58	1.37	4.89	4.95	26.5	95.5	67.1
ICW-SZ-14-15	Lower	SZ	Shrub	17	57	8	62.7	0.37	20.59	13.54	22.37	1.11	1.89	12.22	11.81	0	93.5	38.5
ICW-TH-14-09	Middle	TH	Camo mille	16	80	1	19.8	1.22	1.72	2.89	7.38	0.56	1.39	5.16	5.30	115	61.5	48.0
ICW-TH-14-12	Lower	TH	Camo mille	11	66	1	3.9	1.54	87.80	0.56	1.23	0.15	0.34	3.82	3.56	80.5	64.5	40.0
ICW-TZ-14-02	Upper	WT	Petasites	5	40	4	31.4	0.97	25.49	10.26	11.10	0.97	1.13	10.58	9.81	18.25	90	47.5
ICW-TZ-14-06	Middle	WT	Petasites	16	75	7	21.1	1.27	8.58	6.62	15.99	0.82	1.96	8.08	8.15	0	48.5	10.0
ICW-TZ-14-13	Lower	WT	Petasites	15	45	7	44.5	0.59	2.78	7.89	13.12	0.74	1.22	10.59	10.76	6	78	20.0

Part 2

ID	Latitude	Longitude	slope	NDVI	TWI
ICE-HE-14-12	69,5797620	-138,8729460	1.40	0.69	8.61
ICE-HK-14-11	69,5843090	-138,9001020	4.73	0.67	8.05
ICE-JT-14-15	69,5783430	-138,8931060	5.54	0.56	9.59
ICE-KO-14-01	69,5900100	-138,8999310	1.57	0.66	8.21
ICE-KO-14-07	69,5828090	-138,8782250	10.05	0.67	7.53
ICE-PJ-14-08	69,5829260	-138,8888490	22.67	0.62	7.16
ICE-PJ-14-13	69,5779360	-138,8857230	8.30	0.64	7.30
ICE-SZ-14-10	69,5831580	-138,8924920	5.76	0.73	9.36
ICE-TZ-14-02	69,5892430	-138,8959770	7.26	0.73	7.11
ICE-TZ-14-09	69,5830530	-138,8910850	6.11	0.80	10.31
ICE-TZ-14-14	69,5781480	-138,8891640	14.62	0.78	7.51
ICW-HE-14-01	69,5913950	-138,9142340	6.43	0.74	7.77
ICW-HE-14-08	69,5849750	-138,9161850	5.77	0.68	10.55
ICW-KO-14-05	69,5840600	-138,9046030	8.09	0.63	7.72
ICW-KO-14-14	69,5771460	-138,9044580	2.61	0.66	8.03
ICW-PJ-14-10	69,5901060	-138,9059270	5.31	0.64	7.69
ICW-PJ-14-11	69,5779220	-138,8986600	11.37	0.64	8.06
ICW-SZ-14-15	69,5768320	-138,9007210	7.27	0.63	8.75
ICW-TH-14-09	69,5835900	-138,9122430	4.81	0.57	9.45
ICW-TH-14-12	69,5778170	-138,8994060	26.75	0.58	6.41
ICW-TZ-14-02	69,5907860	-138,9091820	3.64	0.77	8.00
ICW-TZ-14-06	69,5840450	-138,9087640	16.89	0.79	7.80
ICW-TZ-14-13	69,5778330	-138,9009820	6.44	0.69	9.58

R Script

```
# Boxplots for TOC,TN and CN by Ecoclass and Vegclass

par(mfrow = c(1,1))
boxplot(SOC_30cm ~ecoclass,data=icecreek_data, main="TOC (0-30cm)",
 cex.axis=1.5, cex.main=1.8, ylab="TOC (kg/m2)", cex.lab=1.5)
boxplot(SOC_30cm ~vegname,data=icecreek_data, main="TOC (0-30cm)",
cex.main=1.8, cex.axis=1.5)
boxplot(SOC_active ~ecoclass,data=icecreek_data,main="TOC (Active
Layer)",
 cex.main=1.8,cex.lab=1.5,cex.axis=1.5, ylab="TOC (kg/m2)",
xlab="Ecological Class")
boxplot(SOC_active ~vegname,data=icecreek_data, main="TOC (Active
Layer)",
cex.main=1.8, cex.lab=1.5,cex.axis=1.5,xlab="Vegetation Class")
boxplot(TN_30cm ~ecoclass,data=icecreek_data, main="TN (0-30cm)",
cex.main=1.8,  cex.axis=1.5, cex.lab=1.5, ylab="TN (kg/m2)")
boxplot(TN_30cm ~vegname,data=icecreek_data, main="TN (0-30cm)",
 cex.main=1.8, cex.axis=1.5)
boxplot(TN_active ~ecoclass,data=icecreek_data, main="TN (Active
Layer)",
 cex.main=1.8,cex.lab=1.5,cex.axis=1.5, ylab="TN (kg/m2)",
xlab="Ecological Class")
boxplot(TN_active ~vegname,data=icecreek_data, main="TN (Active
Layer)",
 cex.main=1.8, cex.lab=1.5,cex.axis=1.5,xlab="Vegetation Class")
boxplot(CN ~ecoclass,data=icecreek_data, main="CN ratio in topsoil",
cex.main=1.8, cex.lab=1.5,cex.axis=1.5,ylab="CN ratio")
boxplot(CN ~vegname,data=icecreek_data, main="CN ratio in topsoil",
 cex.main=1.8,cex.axis=1.5)
boxplot(depth ~ecoclass,data=icecreek_data, main="Active Layer Depth",
cex.main=1.8,cex.lab=1.5,cex.axis=1.5,
        xlab="Ecological Class", ylab="Active Layer Depth (cm)")
boxplot(depth ~vegname,data=icecreek_data, main="Active Layer Depth",
cex.main=1.8,cex.lab=1.5,cex.axis=1.5,
        xlab="Vegetation Class")
boxplot(CN_30 ~ecoclass,data=icecreek_dataCN, main="CN Ratio (0-30cm)",
cex.main=1.8, cex.lab=1.5,cex.axis=1.5)
boxplot(CN_30 ~vegname,data=icecreek_dataCN, main="CN Ratio (0-30cm)",
 cex.main=1.8,cex.axis=1.5)
boxplot(CN_active ~ecoclass,data=icecreek_dataCN, main="CN Ratio
(Active Layer)",
cex.main=1.8, cex.lab=1.5,cex.axis=1.5)
boxplot(CN_active ~vegname,data=icecreek_dataCN, main="CN Ratio (Active
Layer)",
 cex.main=1.8,cex.axis=1.5)
```

```
# Boxplots for Transects

par(mfrow = c(2,2))
boxplot(SOC_30cm ~streamsection,data=icecreek_data, main="TOC (0-
30cm)",
        xlab="Stream Section", ylab="TOC (kg/m2)",cex.main=1.8,
cex.lab=1.5,cex.axis=1.5)
boxplot(TN_30cm ~streamsection,data=icecreek_data, main="TN (0-30cm)",
        xlab="Stream Section", ylab="TN (kg/m2)", cex.main=1.8,
cex.lab=1.5,cex.axis=1.5)
boxplot(CN ~streamsection,data=icecreek_dataCN, main="CN Ratio (0-
30cm)",
        xlab="Stream Section", ylab="CN Ratio", cex.main=1.8,
cex.lab=1.5,cex.axis=1.5)
boxplot(CN_30 ~streamsection,data=icecreek_streamCN, main="CN Ratio
Creek (0-30cm)",
        xlab="Stream Section", ylab="CN Ratio", cex.main=1.8,
cex.lab=1.5,cex.axis=1.5)


# Example Anova and Tukey post hoc test
depth.aov <- aov(icecreek_data$depth~icecreek_data$vegname)
summary(depth.aov)
TukeyHSD(depth.aov)


# Spearmann correlation matrix

cor(spearmann, method= c("spearman"))
rcorr(X, type=c("spearman"))
X<-as.matrix(spearmann)
```

```
#PCA ECO CLASS

#Create category
ecoclass <- ice_creek_select[, 3]

#define columns
soil<-ice_creek_select[, 6:21]

#run PCA
soil.pca <- prcomp(soil,
                   center = TRUE,
                   scale. = TRUE)
#display PCA
print(soil.pca)
library(devtools)
install_github("ggbiplot", "vqv")
library(ggbiplot)
g <- ggbiplot(soil.pca, obs.scale = 1, var.scale = 1,
              groups = ecoclass, ellipse = TRUE,
              circle = FALSE,
              varname.size = 6,colour = "black", varname.adjust = 1.5)
g <- g + geom_point(aes( shape = groups, color = groups), size=5, ) +
      scale_shape_manual(values = 0:length(unique(ecoclass)))+
scale_colour_manual
      (values = c("blue","dark blue", " dark green","Yellow","brown",
"red", "green"))
g<- g + theme_bw()
print(g)
```

NMDS

```
dat <- ice_creek_vegetation
dat

plot(dat)
attach(dat)
names(dat)

library(permute)
library(vegan)
library(MASS)

veg.pca<-rda(dat[,3:53])
veg.pca

head(veg.pca)

envdat<-dat[,1:2]
envdat
envi_pca<-envfit(veg.pca, envdat, permu=999, na.rm=TRUE)

veg.pca <- dat[,1:53]
plot(veg.pca)

veg.dis<-vegdist(dat[,3:53])
veg.mds0<-monoMDS(veg.dis)
stressplot(veg.mds0, veg.dis)
ordiplot(veg.mds0, type="t")

envdat<-dat[,1:2]
envdat
envi_mds<-envfit(veg.mds0, envdat, permu=999, na.rm=TRUE)
envi_mds
plot(envi_mds, p.max=0.2)

veg.mds<-metaMDS(dat[,3:53])
veg.mds

head(veg.mds)
attach(dat)
par(mfrow=c(1,1))
plot(veg.mds,display=c("species"), type="n", xlim=c(-2,2), ylim=c(-
1.5,1.5))

points(veg.mds, display=c("sites"), choices=c(1,2), select=Type=="HE",
col="green", pch=1)
points(veg.mds, display=c("sites"), choices=c(1,2), select=Type=="HK",
col="blue", pch=2)
points(veg.mds, display=c("sites"), choices=c(1,2), select=Type=="KO",
col="brown", pch=3)
points(veg.mds, display=c("sites"), choices=c(1,2), select=Type=="TH",
col="purple", pch=4)
points(veg.mds, display=c("sites"), choices=c(1,2), select=Type=="PJ",
col="darkblue", pch=5)
points(veg.mds, display=c("sites"), choices=c(1,2), select=Type=="SZ",
col="black", pch=6)
```

```
points(veg.mds, display=c("sites"), choices=c(1,2), select=Type=="TZ",
col="pink", pch=7)
points(veg.mds, display=c("sites"), choices=c(1,2), select=Type=="NN",
col="red", pch=8)

legend(x=1.5,y=1.8, cex= 0.8, c("Herschel", "He-Komakuk",
"Komakuk","Thrasher",
      "Plover Jaeger", "Shrub Zone", "Transitional", "not known"),
col=c("green","blue",
      "brown","purple", "darkblue","black","pink","red"),
pch=c(1,2,3,4,5,6,7,8) )

#GGPLOT for NMDS
data.scores <- as.data.frame(scores(veg.mds))
site<-ice_creek_vegetation$Point
data.scores$site <- site
Type <- ice_creek_vegetation$Type
data.scores$Type <- Type
head(data.scores)

species.scores <- as.data.frame(scores(veg.mds, "species"))
species.scores$species <- rownames(species.scores)
head(species.scores)

library(ggplot2)

data.scores$Type <- factor(data.scores$Type)

ggplot() +
geom_point(data=data.scores,aes(x=NMDS1,y=NMDS2,shape=Type,colour=Type)
,size=4) + scale_shape_manual(values=1:nlevels(data.scores$Type))+
      geom_vline(aes(xintercept=0))+
      geom_hline(aes(yintercept=0))+
  +  # add the site labels
  scale_colour_manual(values=c("HE" = "blue", "HK" = "dark blue", "KO"=
"dark green",
      "TH"="red", "PJ"="yellow", "SZ"="brown", "TZ"="green")) +
  coord_equal() +
  theme_bw()+
  theme(axis.text.x = element_blank(),  # remove x-axis text
        axis.text.y = element_blank(), # remove y-axis text
        axis.ticks = element_blank(),  # remove axis ticks
        axis.title.x = element_text(size=18), # remove x-axis labels
        axis.title.y = element_text(size=18), # remove y-axis labels
        panel.background = element_blank(),
        panel.grid.major = element_blank(),  #remove major-grid labels
        panel.grid.minor = element_blank(),  #remove minor-grid labels
        plot.background = element_blank())
```

Eidesstattliche Erklärung

Hiermit versichere ich an Eides statt, dass ich die Masterarbeit selbständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt und die aus fremden Quellen direkt oder indirekt übernommenen Gedanken als solche kenntlich gemacht habe. Die Arbeit habe ich bisher keinem anderen Prüfungsamt in gleicher oder vergleichbarer Form vorgelegt. Sie wurde bisher auch nicht veröffentlicht. Ich erkläre mich damit einverstanden, dass die Arbeit mit Hilfe eines Plagiatserkennungsdienstes auf enthaltene Plagiate überprüft wird.

Ort, Datum Isabell Eischeid