ORGANIC MATTER QUALITY IN CRYOSOLS: EFFECT ON SOIL NITROGEN DYNAMICS AND GREENHOUSE GAS EMISSIONS

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By

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Abstract

Over the past millennia, complex terrestrial ecosystems have evolved in the Arctic. However, the stability of these unique ecosystems is in jeopardy because of climate changes. Due to the fact that Arctic soils store great amounts of carbon (C) in soil organic matter (SOM), any change that may occur in SOM with climate changes may substantially affect many aspects of Arctic ecosystems such as vegetation, animals, and humans. On a more global perspective, any change in Arctic SOM has the potential of modifying the overall world climate by affecting the global greenhouse gas (GHG) budget. A better understanding of the soil factors that affect soil N and C cycling at the landscape scale, such as moisture, temperature, and SOM characteristics, is necessary to produce better models. The overall objective of this study was to characterize the properties of SOM in Arctic soils and their influence on soil N and C cycling dynamics – including GHG emissions – at the landscape scale.

This study was conducted in three distinct Arctic ecosystems: Sub-Arctic (Churchill, MB), Low-Arctic (Daring Lake, NWT), and High-Arctic (Truelove, NU). For each site, the sampling locations were evenly divided into five landform units: 1) upper slope (Up), 2) back slope (Back), and 3) lower slope (Low) for catena sites, and 4) hummock (Hum) and 5) wedges of hummock (W) for hummocky sites (i.e., hummock in Churchill and ice-wedge polygons in Truelove). All sites were sampled at the end of their growing season (from 2 to 3 weeks before plant senescence). The characteristics of SOM were assessed using three methods: 1) density fractionation to separate the uncomplexed light fraction (LF) from heavy fraction (HF) of SOM (LF < 1.55 g mL^{-1} < HF), 2) solid-state CPMAS ^{13}C nuclear magnetic resonance (NMR) spectroscopy that determined the relative proportions of carbonyl-C (CbyC), alkyl-C (AC), aromatic-C (AroC), o-alkyl-C (OAC), and carbohydrates-C (CC), and 3) water-extractable organic matter (WEOM) that estimated SOM diluted in soil solution. Soil gross N mineralization was measured *in situ* using ^{15}N dilution technique. Soil GHG emissions [nitrous oxide (N_2O), methane (CH_4), and carbon dioxide (CO_2)] were measured *in situ* using a multicomponent Fourier transform infrared gas analyzer coupled with an automated dark chamber.

The first study showed that organic surface soils, which had more than 17% soil organic C (SOC) by weight, contained relatively more labile SOM than mineral surface soils (< 17% SOC). For example, OAC:AroC ratios of the organic soils ranged from 25 to 75% greater compared to mineral soils. At Churchill, Daring Lake, and Truelove, 53, 73, and 20% of the C and N was included in the LF, respectively. All results show that the organic soils of Sub- and Low-Arctic ecosystems sampled for this study contain more fresh and un-decomposed plant residues than High-Arctic organic soils. The second study showed that both topography and ecosystems had a significant impact on gross N mineralization and CO_2 emission rates. For example, at Churchill, gross N mineralization increased about 6-fold from upper slope to lower slope areas. Similarly, at Daring Lake, CO_2 emissions increase about 5-fold from upper slope to lower slope areas. Topography and ecosystems had a very limited impact on soil N_2O and CH_4 emissions most likely because net emissions were extremely low. The third study showed that soil moisture, SOM quantity, and labile SOM parameters such as OAC:AroC and water-soluble organic carbon (WSOC) positively influenced gross N mineralization, N_2O, and CO_2 emissions, whereas the relative proportion of AroC negatively influenced gross N mineralization, N_2O, and CO_2 emissions. Relationships between SOM characteristics and CH_4 emissions were not significant. This study showed that Up and Back areas tended to store relatively more recalcitrant SOM (AroC) than Low, Hum, and W areas, suggesting less fresh plant input on these landform units.

Assessing SOM qualities with the ability of the soils to mineralize N (i.e., gross N mineralization) and release GHG at the landscape scale and across the Arctic represents a great advance in the understanding of these complex and unique ecosystems. Lower proportion of fresh and labile SOM found on Up and some Back landform units compared to Low and hummocky sites suggest that plants have more difficulties establishing and growing on these landform units (e.g., Up and Back) that experience harsh climates. Therefore, generalizations of the climate change impacts on soil N and C cycling processes throughout Arctic landscapes and ecosystems are less certain if topography is not considered. These results are particularly important because they can be used to produce better models that evaluate SOM stocks and dynamics under several climate scenarios and across Arctic landscapes and ecosystems.

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My gratitude also goes to many individuals from the Soil Science Department who helped me technically and morally with this great adventure. Special thanks to my office-mates, Samiran Banerjee and Tom King. Thanks also to Cory for Burgers and football days, Ryan for hockey goals, Hangs' family for perseverance, Jay and Alexis for baseball games and hiking trips, and Darwin and Donna for great tennis matches.

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Dedication

Je désire dédier cette thèse à ceux et celles pour qui l'intégrité et l'honnêteté sont deux aspects fondamentales dans la pratique de la science. À ceux et celles pour qui décrire la réalité n'est pas un exercice sensationnel et extraordinaire mais bien un privilège qu'il faut accomplir le plus méticuleusement et honnêtement possible.

Plus personnellement, je dédie cette thèse à une personne qui m'a permis de réaliser quelques rêves, à une personne qui m'a toujours supporté, à mon ange bien réel, à mon amour, Julie Guérin.

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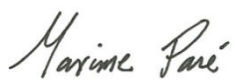
List of Abbreviations

AC	Alkyl-C
AroC	Aromatic-C
CbyC	Carbonyl-C
CC	Carbohydrates-C
DOC	Dissolved organic carbon
DOM	Dissolved organic matter
DON	Dissolved organic nitrogen
GHG	Greenhouse gas
Hum	Hummock
HF	Heavy fraction
IPY	International polar year
Low	Lower slope
LF	Light fraction
MC	Methoxyl-C
NMR	Nuclear magnetic resonance
OAC	O-Alkyl-C
POM	Particulate organic matter
SOC	Soil organic carbon
SOM	Soil organic matter
TN	Total nitrogen
Up	Upper slope
W	Wedge of hummock
WEOM	Water-extractable organic matter
WSOC	Water-soluble organic carbon
WSOM	Water-soluble organic matter
WSON	Water-soluble organic nitrogen
WSN	Water-soluble nitrogen

Preface and Foreword

This research project was a tiny portion of the International Polar Year (IPY), which was a large scientific programme that focused on the Arctic and the Antarctic from March 2007 to March 2009. The concept of the IPY was an intensive burst of internationally coordinated, interdisciplinary, scientific research and observations focused on the Earth's Polar Regions, regrouping many countries such as Canada, the United-States, Finland, Norway, Denmark, and Russia.

This dissertation is structured into eight chapters. The first chapter presents a general introduction and a "*mise en contexte*" of the study. Chapter two presents a literature review of the concepts and methods that were used throughout this dissertation. The next three chapters are where most of the scientific work was done. Chapter three assesses soil organic matter qualities from several Arctic soils and ecosystems. Thereafter, chapter four investigates how soil carbon and nitrogen cycling processes vary throughout Arctic landscapes. Finally, chapter five relates soil organic matter characteristics and soil carbon and nitrogen cycling processes at the landscape scale. The dissertation ends with an overall conclusion (Chapter 6), a list of cited references (Chapter 7), and appendices (Chapter 8). This manuscript represents a major advance in our understanding of Arctic soil carbon and nitrogen cycling processes. Furthermore, this work should help both Northerners and scientists to better predict and explain the impacts of climate change on soil organic matter and life that Arctic soils are supporting.



Bonne lecture!

Chapter 1 : Introduction

The Arctic is the most beautiful, peaceful, and quiet area that I have ever visited. Numerous animals, plants, and humans depend on this fragile part of the globe. Because of the diversity that Arctic landscapes offer (e.g., ponds, small lakes, sedge meadows, bogs, and ridges), many birds travel several thousand kilometres each year to nest and feed in the Arctic. Other animals, such as foxes, wolves, caribous, weasels, and lemmings permanently use the terrestrial Arctic as their habitat. The diversity of habitats found in the Arctic offers a wide variety of plant species, of which many are exclusively found in Arctic ecosystems. Therefore, although the Arctic appears *à priori* peaceful and quiet, extremely complex biological ecosystems have successfully evolved, despite cold temperatures and extreme weather events. Unfortunately, the stability of these unique ecosystems is in danger; the climate is changing.

The Arctic climate system is very complex and is affected by many factors such as sea ice, complex dynamics and thermodynamics and polar atmosphere stratification (e.g., dryness of the air and multiple cloud layers). Nevertheless, from 1990s to the 2090s, conservative models predict that the mean annual precipitations will increase by 12% and the mean annual air temperatures will minimally rise up to 5 °C for most of the Canadian Arctic terrestrial areas (Huntington et al., 2005; Kattsov et al., 2005). There are many uncertainties about Arctic climates and ecosystems but new data will continue to be gathered from a wide range of approaches and models. The data will provide a better understanding of the complex processes, interactions, and feedbacks, and will undoubtedly improve our confidence of what the expected impacts are likely to be in the Arctic (Huntington et al., 2005).

One of the most important aspects of the impact of climate changes in the Arctic will be the modification of the basis of the food chain: the vegetation. Warmer climate conditions in the Arctic will undoubtedly shift plant species from south to north. However, this plant migration will not occur uniformly throughout Arctic landscapes. Physical and biological conditions vary greatly across the Arctic, contributing to different impacts and responses to climate change at a variety of spatial scales (Huntington et al., 2005). Certainly, plant migration in the Arctic will

depend upon many factors such as the availability of nutrients (e.g., nitrogen). However, warmer climates could also trigger a large release of greenhouse gases (GHG) into the atmosphere via soil organic matter (SOM) decomposition – therefore enhancing the climate change effect. Better understanding of soil carbon (C) and nitrogen (N) cycling processes in Arctic soils is required to accurately predict climate change effects on Arctic terrestrial ecosystems.

Three major factors have been identified affecting the soil C and N cycling processes of Arctic soils: 1) moisture, 2) temperature, and 3) SOM qualities. While the effects of soil moisture and temperature are well documented, the effect of SOM qualities is still less understood. Although I will briefly consider the effects of moisture and temperature, this thesis will focus mainly on SOM qualities.

The overall objective of this study is to characterize the properties of SOM in Arctic soils and their influence on soil N and C cycling dynamics. The scientific work is sub-divided into three distinct studies. The specific objectives of this study are to 1) characterize SOM qualities from Arctic soils, 2) determine how Arctic SOM characteristics differs between mineral and organic soils, 3) determine how Arctic SOM characteristics differs among three Arctic ecosystems, 4) investigate how soil gross N mineralization and GHG emissions vary across landscapes and Arctic ecosystems, and finally 5) investigate the influence of soil properties and SOM characteristics on soil gross N mineralization and GHG emissions at the landscape scale. Assessing these factors with the ability of the soils to provide N and release GHG at the landscape scale and across the Arctic will mean great advances in our understanding of these complex and unique ecosystems.

Chapter 2 : Literature Review

2.1 Soil Organic Matter

The soil organic matter (SOM) is composed of various detritus from plants, animals, and soil microbes. From an agronomy perspective, the level of SOM is generally a strong indicator of soil quality: SOM-rich soils are considered fertile, whereas soils lacking in SOM are considered poor and infertile (Bauer and Black, 1994; Haynes and Naidu, 1998; Reeves, 1997). From a soil ecology perspective, the level of SOM can also be related to soil health: soils with high SOM contents have great soil microbial biomass activity and diversity compared to soils with low SOM contents (Kaiser et al., 1992; Powlson and Brookes, 1987; Schnürer et al., 1985). Therefore, SOM is generally one of the first measured soil parameters in various disciplines interested in soil properties and general ecosystem health.

2.1.1 Soil Organic Matter in the Arctic

Arctic soils tend to accumulate great amounts of SOM. Recently it was estimated that Arctic soils store approximately 60% of the SOM in all soils of North America, which represents 25% of the SOM stored in all soils of the entire world (Tarnocai et al., 2008). In Arctic soils, SOM is a great nutrient store. For example, the total ecosystem C content can be partitioned into 1.5-3.0% in the microbial biomass, 10-17% in the plants and the remaining 81-88% in the dead part of SOM (Schmidt et al., 2002). In Arctic ecosystems dominated by dwarf shrubs, 90 to 95% of the N was incorporated in different pools of SOM (Jonasson, 1983; Jonasson et al., 1999). Therefore, SOM is the principal C and N store in Arctic soils and understanding its dynamics is important to determine if the Arctic will be either a net C sink or a net C source in response to global warming.

2.1.2 The Functions of Soil Organic Matter

The roles of SOM in soil are diverse and extremely important. For example, SOM increases water-retention capacities of coarse-textured soils and reduces the severity of drought (Hudson, 1994). In heavier soils, SOM improves soil structure (e.g., aggregates) and hence increases soil air permeability (Chaney and Swift, 1984; Oades, 1984; Tisdall and Oades, 1982). Chemically, SOM can act as a soil nutrient reserve by storing and adsorbing soil nutrients such as nitrogen (N) and phosphorus (P) (Helling et al., 1963; Lax et al., 1986; McGill and Cole, 1981; Zech et

al., 1997). In addition, SOM may attenuate the toxicity of heavy metals and toxic organic compounds (Schnitzer, 1991). Biologically, SOM provides nutrients and energy to numerous soil microorganisms. This decomposition of SOM transforms organic N and P forms into more plant-accessible mineral forms such as ammonium (NH_4^+) and orthophosphates (e.g., $H_2PO_4^-$, HPO_4^{2-}, PO_4^{3-}). Alternatively, the decomposition of SOM by soil microbes produces carbon dioxide (CO_2), methane (CH_4), and nitrous oxides (N_2O), which are three potent greenhouse gases (GHG) contributing to climate change (Huntington et al., 2005). In soil, three factors affect SOM decomposition: moisture, temperature, and SOM qualities. Although the qualities of SOM are a major control on SOM mineralization in Arctic ecosystems (Nadelhoffer et al., 1991), little is known about SOM qualities of Arctic soils and how SOM qualities may ultimately influence soil N and C cycling processes. Therefore, a better understanding of Arctic SOM qualities is needed.

2.1.3 Characterizing Soil Organic Matter

Soil organic matter is a heterogeneous mixture of naturally occurring organic compounds from plants, animals, and microbes (Mahieu et al., 1999). Most of compounds found in this mixture such as cellulose, hemicelluloses, and proteins are easy to decompose (i.e., labile), whereas other compounds such as lipids and esters are much more refractory in nature (i.e., recalcitrant) (Paul et al., 2001; Trumbore, 1993). Moreover, this mixture of organic compounds (i.e., SOM), can be mineralized or transformed into a series of complex and more recalcitrant molecules by soil microorganisms (Bollag et al., 1998). This process is called SOM decomposition. Laboratory incubations using ^{13}C techniques and soil from Low-Arctic regions have shown that soil microorganisms mineralize the most labile C first and another microbial population uses more recalcitrant C thereafter (Oelbermann et al., 2008). Therefore, labile fraction of SOM, in opposition to recalcitrant fraction, is defined as the fraction of SOM that is easy to decompose by soil microorganisms.

The SOM can be found in two main soil components: 1) solid soil and 2) soil solution. The solid SOM is defined as the fraction of the soil (< 2mm) that includes a wide range of compounds such as plant, animal, and microbe residues (e.g., cells, tissues, and metabolites) at various stages of decomposition. The soil-solution SOM includes all water-soluble organic matter (WSOM) (< 0.45 μm) found in the soil solution.

Most of the materials included in SOM could be either unprotected or protected by three major soil processes: 1) chemical, 2) physical, and 3) biochemical (Gregorich et al., 1994; Six et al., 2002) (Table 2.1).

Table 2.1: Soil organic matter protection processes. †

Protection Processes	Type of Protection
Chemical	SOM protected by clay and silt Physico-chemical barriers against microbes Clay (2:1) > Clay (1:1) ex: montmorillonite vs. kaolinite
Physical	SOM protected by aggregates Physical barriers against microbe ex: microaggregates > macroaggregates
Biochemical	SOM protected by its composition Chemical barriers against microbes ex: lignin > sugars

† Information adapted from Six et al. (2002).

The chemical and physical protection processes are less affected by SOM composition, whereas biochemical protection is determined by its chemical nature. To be available to soil heterotrophic microbes, SOM needs to be accessible – not protected by soil chemical and physical protection processes – and labile enough to be consumed by heterotrophic soil microbes (e.g., sugar is more labile than lignin). In active surface soils, adsorption (i.e., chemical protection process) and aggregation (i.e., physical protection process) can delay decomposition processes but molecular recalcitrance (i.e., biochemical protection process) is the only mechanism by which SOM can be stabilized for long periods of time (Krull et al., 2003). Therefore, assessing the biochemical protection process by determining the chemical structures of SOM materials is essential to clearly determine SOM characteristics.

Soil organic matter is usually subdivided into two groups: 1) nonhumic and 2) humic substances. Nonhumic substances are organic compounds that are still recognizable chemical compounds such as carbohydrates, proteins, peptides, and amino acids. Nonhumic substances are strongly active in C and N cycling processes because these compounds are highly degradable in soils and have short life spans (Schnitzer, 1991). Alternatively, humic substances are amorphous, dark-colored, and partly aromatic substances. Humic substances are more resistant than nonhumic materials to chemical and biological degradation and hence have long residence times (Schnitzer,

1991; Schnitzer, 2001). Therefore, humic substances represent a more stable soil C pool over time than nonhumic substances. They also play a less-important role in rapid C and N cycling processes than nonhumic substances. The distinction between nonhumic and humic pools is essential to select an appropriate method to characterize and quantify SOM qualities.

2.1.4 Quantifying Soil Organic Matter Qualities

To improve SOM models we need to link conceptual model pools to functional SOM fractions that are measured by distinct techniques. Several techniques have been proposed to characterize SOM qualities (Table 2.2).

Fractionation of humic substances and characterization by chemical methods are useful to determine recalcitrant pools of SOM (e.g., organic acids and carbonyl/hydroxyl groups present in humic substances). Alternatively, density fractionation of SOM, characterization by spectroscopy, and water extraction of SOM are three useful methods that quantify and characterize labile and fresh components of SOM (e.g., nonhumic substances active in C and N cycling processes). In addition, because no corrosive chemical is used to separate SOM pools, the latter methods are considered as less "destructive" and better represent the un-stable (i.e., biologically active), partly decomposed, and labile molecules of SOM. Furthermore, some of the techniques used to determine the SOM qualities, such as density fractionation, assess all three protection processes, whereas other techniques such as solid-state ^{13}C nuclear magnetic resonance (NMR) only focus on the biochemical protection process. Density fractionation of SOM, spectroscopy (e.g., ^{13}C NMR), together with water extraction of SOM are three suitable techniques to characterize Arctic SOM characteristics when soil N and C cycling processes are studied. These three SOM fractionation techniques will be covered in more detail.

Table 2.2: Summary of the major techniques developed to characterize soil organic matter (SOM) characteristics.

Technique	SOM Group	Principle
Chemical		
Solubility	Humic	Solutions with various pHs (fulvic & humic acids & humin)
Molecular size		Gel permeation chromatography & ultra-filtration
Charge Characteristics		Electrophoresis
Physical		
Density	Nonhumic & Humic	Heavy liquid (LF and HF)
Particulate		Heavy liquid & sieving (POM†)
Spectroscopy		
Ultraviolet-visible	Nonhumic & Humic	Absorption UV (200-400 nm) & Visible (400-800 nm) by molecule
Infrared		Molecular vibrations
Nuclear magnetic resonance		Nuclei magnetic spin
Electron spin resonance		Electromagnetic radiation of molecules with unpaired electrons (free radicals)
Fluorescence		Fluorescence emitted (wavelength) after UV-visible radiation
Water Extraction		
Water-extractable organic matter	Nonhumic & Humic	Incubation of soil in water
Dissolved organic matter		Lysimeter

† Particulate Organic Matter found in different size-fractions of the soil. Information summarized from Swift (1996) and Chantigny (2003).

2.1.4.1 Characterization of SOM by Physical Fractionation Techniques

Physical fractionation techniques separate SOM from soil on the basis of density and/or size. Separation by density – using heavy liquids – extracts or separates SOM particles that are not bound to mineral soil particles (Gregorich et al., 2006; Six et al., 2002). This fraction is often referred to as physically uncomplexed or unprotected SOM. Alternatively, separation by size – a combination of heavy liquids, dry, and wet sieving techniques – separates SOM that are bound to different soil particles and sizes (Six et al., 2000). This fraction is often referred to particulate organic matter (POM). Therefore, physically unprotected SOM plays a greater role than POM in rapid N and C cycling processes such as N mineralization and soil GHG emissions because physically unprotected SOM is more accessible to soil microorganisms for degradation and decomposition than the physically protected POM (Gregorich et al., 2006).

The density fractionation method to separate physically uncomplexed SOM is based on the weight per unit volume of SOM (i.e., density) and is independent of size and shape of the SOM (Elliott and Cambardella, 1991). The density fractionation technique separates fresh and partially-decomposed SOM from organo-mineral materials. The concept behind density separation assumes that organic matter can be divided into fractions differing in structure and function (Meijboom et al., 1995). This type of separation divides the SOM according to age, where the younger and older fractions of SOM are generally in the light (LF) and heavy (HF) fractions, respectively (Swift, 1996). The LF is intermediate between plant litter and more stable humic substances and the rate of loss (i.e., decomposition rate) is much greater from the LF than from the HF of SOM (Zech et al., 1997). Therefore, the fresh and partly decomposed residues found in the LF are generally more labile than the residues found in HF of SOM. When compared with conventional acid-base SOM extractions (e.g., humic substance and chemical methods), density fractionation avoids the need for solvents, decreases the probability of artefact formation (Swift, 1996), and extracts those fresh and unstable pools of SOM responsible for rapid N and C cycling rates in a more efficient manner.

Using an appropriate density for SOM separation is an important aspect of this technique because different liquid densities can result in major differences of SOM fraction extracted (Gregorich et al., 2006). Spycher et al. (1983) demonstrated that, compared to 1.8 g cm^{-3}, using 1.65 g cm^{-3} as liquid density considerably reduced organo-mineral particles (i.e., mineral contaminants) found in the LF. Similarly, Sollins et al (1984) defined $SOM_{<1.6\ g\ cm\text{-}3}$ as undecomposed plant debris and $SOM_{>1.6\ g\ cm\text{-}3}$ as the light organo-mineral complex fraction. More recently, Gregorich and Beare (2008) recommended 1.7 g cm^{-3} as the standard density for temperate soil ecosystems (e.g., agricultural and forest soils) and considered $SOM_{<1.7\ g\ cm\text{-}3}$ as the intermediate fraction of SOM between fresh plant residues and more stabilized SOM. However, $SOM_{<1.7\ g\ cm\text{-}3}$ may constitute a major proportion of the SOM, especially in natural ecosystems such as the Arctic where $SOM_{<1.7\ g\ cm\text{-}3}$ constitutes more than 70% of the whole SOM (Gundelwein et al., 2007). Based on these two criteria: 1) the difference between the C:N values of the LF and HF needs to be as large as possible and 2) the C:N value of the whole soil needs to be different from the C:N values of the LF and HF, Paré and Bedard-Haughn (2011) recently found an optimum liquid density of 1.55 g cm^{-3} to separate LF and HF of SOM from three distinct Canadian Arctic ecosystems (Appendix A).

2.1.4.2 Characterization of SOM by Spectroscopy Techniques

Alternative techniques for the examination of SOM are non-destructive spectroscopic methods, which include ultraviolet-visible, nuclear magnetic resonance (NMR) spectroscopy, infra-red spectroscopy, electron spin resonance spectroscopy, and fluorescence (Table 2.2). The advantage of such techniques lies in the fact that the sample can be analyzed without major pre-treatment and extraction (Kögel-Knabner, 2000). Alternatively, specific compounds or structures are not identified specifically making spectroscopy techniques relatively insensitive (i.e., low resolution) compared to most techniques that involve chemicals and/or heat. Compared to other studies that characterized SOM using ultraviolet-visible (Kalbitz et al., 2003), infra-red spectroscopy (Henderson et al., 1992; Krishnan et al., 1980), electron spin resonance spectroscopy (Bayer et al., 2000), and fluorescence (Chen et al., 2003), NMR spectroscopy is now a widely used technique to characterize SOM and SOM fractions in various areas such as soil chemistry, soil pedology, soil microbiology, and soil fertility (Preston, 2001; Simpson and Preston, 2008;

Skjemstad et al., 1997). Therefore, comparisons among studies, sites, and ecosystems are facilitated when the NMR spectroscopy technique is used.

Analysis by ^{13}C NMR spectroscopy appears to be well-suited for obtaining an inventory of the chemical composition of SOM because it provides information regarding the relative proportion of the entire organic C spectrum from O-Alkyl-C (OAC), Aromatic-C (AroC), Alkyl-C (AC), to Carbonyl-C (CbyC) (Dria et al., 2002; Schnitzer, 1991; Simpson and Preston, 2008). Therefore, ^{13}C NMR spectroscopy is the prefered technique to use (in our Arctic SOM context) when a first approximation of SOM chemistry is needed (i.e., little is known about SOM qualities).

Two main NMR instrument groups are used in SOM studies: 1) solid-state NMR and 2) liquid-state NMR. Solid-state NMR is used for solid samples (e.g., soil samples) and liquid-state NMR is used for liquid samples (e.g., WEOM). The principles behind NMR techniques are relatively complex. For those interested in deep understanding of NMR spectroscopy, Kinchesh et al. (1995) published an excellent review of this technique. A simplified definition as written by Gregorich et al. (2001, p. 244) stated that NMR is:

> "A spectroscopic technique measures the absorption of radiofrequency (RF) radiation by a nucleus in a strong magnetic field. Absorption of the radiation causes the nuclear spin to realign or flip in the higher-energy direction. After absorbing energy, the nuclei will reemit RF radiation and return to the lower-energy state. The energy of an NMR transition depends on the magnetic field strength and a proportionality factor for each nucleus, called the magnetogyric ratio. […] The local environment around a given nucleus in a molecule will slightly perturb the local magnetic field exerted on that nucleus and affect its exact transition energy. This dependence of the transition energy on the position of a particular atom in a molecule makes NMR spectroscopy extremely useful for determining the structure of molecules."

Mathematically, the NMR frequency of a given nucleus (^{13}C) (v sample) is measured relative to a standard [adamantane ($C_{10}H_{16}$)] and the frequency for the resonance is given as the difference (or chemical shift, δ) between these two frequencies, expressed in parts per million (ppm) (Swift, 1996):

$$\delta = \left(v_{sample} - v_{reference}\right) * \frac{10^6}{v_{reference}} \quad (2.1)$$

Although there is a possibility to divide spectra range into several parts or chemical shifts, Table 2.3 outlines the most common spectra ranges used for SOM characterization.

Table 2.3: Chemical shift, region names, and chemical content of soil organic matter determined by solid-state ^{13}C NMR spectroscopy. †

Chemical shift, ppm	Region name	Chemical content
0-45	Alkyl-C (AC) (aliphatic)	Lipids Fatty acids Plant polymers
45-110	O-alkyl-C (OAC)	Cellulose, Hemicelluloses Methoxyl-C Proteins Carbohydrates Side chains of lignin and protein
110-160	Aryl-C (aromatic) (AroC)	Lignin derived molecules Protein derived molecules
160-220	Carbonyl-C (CbyC)	Esters Carboxyl groups Amide Carbonyls

† Information adapted from Helfrich et al. (2006), Simpson and Preston (2008), and Blumfield et al. (2004).

Several functional C groups of SOM are identified by solid-state ^{13}C NMR spectroscopy. Paraffinic Alkyl-C is present in plant polymers and lipids (e.g., cutin and suberin); O-alkyl-C (e.g., plant polysaccaharides) is labile substrate to a large number of fungi and bacteria; aromatic-C are molecules mostly derived from lignin decomposition; and carbonyl-C structures also originate from lignin transformation (Kögel-Knabner, 2002). The OAC group generally is dominated by signals from celluloses and other polysaccharides (e.g., carbohydrates-C) compounds readily decomposed by soil microbes. The AC, AroC, and CbyC groups tend to decompose slowly (Lützow et al., 2006; Skjemstad et al., 1997; Sollins et al., 1996). Sjögersten et al. (2003) found that tundra soils contain a large proportion of highly labile SOM (i.e., O-alkyl-C), suggesting that SOM from Arctic will be highly degradable under more suitable conditions (i.e., improved availability of thermal energy and moisture).

A long-term experiment showed that the OAC group in soil was strongly affected by both vegetation and soil management, whereas more recalcitrant C groups (i.e., AC and AroC)

determined by ^{13}C NMR spectroscopy were stable throughout the experiment (Kinchesh et al., 1995). Because soil microbes selectively degrade the less recalcitrant compounds first (i.e., labile SOM) (Baldock et al., 1992; Sollins et al., 1996) (Figure 2.1), a three-step model of oxidative SOM decomposition using chemical shift (i.e., C groups) obtained from solid-state ^{13}C NMR has been proposed (Baldock et al., 1992; Quideau et al., 2000):

1. The labile SOM structure such as carbohydrates, celluloses, and hemicelluloses are preferentially degraded into aromatic and more recalcitrant organic compounds: decreasing OAC signals and increasing AroC signals.

2. Once the OAC has been degraded, aromatic organic compounds such as lignin are decomposed: decreasing AroC signals.

3. The third and final stage of decomposition is characterized by the accumulation of Alkyl-C organic compounds: increasing AC signals.

Therefore, C-group ratios such as OAC:AroC and OAC:AC as determined by ^{13}C NMR spectroscopy are good indicators of the overall characteristic or biochemical composition of SOM. However, as highlighted by Baldock et al. (1992), plants may produce some recalcitrant molecules such as polymethylene. Therefore, C-group ratios as determined by solid-state ^{13}C NMR cannot be a stand-alone technique to evaluate SOM qualities. Other techniques that support NMR findings are required.

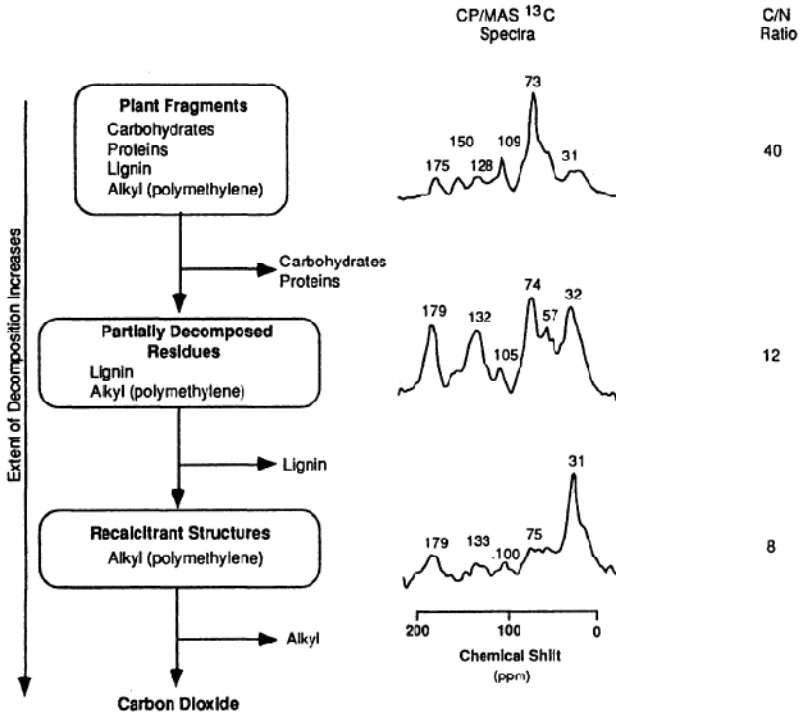


Figure 2.1: A simple model describing the oxidative decomposition of SOM from plant residues to more stable SOM. Figure adapted from Baldock et al. (1992).

2.1.4.3 Characterization of SOM by Water Extraction Techniques

Characterization of SOM by water extraction techniques separate SOM that is dissolved in water and that can pass through a 0.45 μm filter (Chantigny et al., 2008). In the literature, studies often differ in how to extract SOM that is dissolved in water. Because different extraction methods may lead to differences in collected fractions, careful selection of technique is needed. There are two major ways to estimate SOM that is dissolved in water. Directly, dissolved organic matter (DOM) is removed from soil solution by using specialized field equipment such as lysimeters. The DOM collected with such methods most closely represents the SOM that is found in nature. Indirectly, soil is mixed with water and water-extractable organic matter (WEOM) is extracted from this solution after being filtered (0.45 μm). Although indirectly determined, WEOM is considered an acceptable surrogate to soil solution (i.e., DOM) (Chantigny et al., 2008; Zsolnay, 2003). The installation of heavy equipment to collect DOM is time consuming and not well-

adapted to short-term Arctic studies. Therefore, WEOM is often preferred to DOM. In soil, WEOM concentrations represent a tiny portion of SOM and its concentrations vary in the order: forest > grassland > arable, mostly due to different vegetation types (Chantigny, 2003). Consequently, both the origin of SOM (i.e., type of vegetation) and the degree of SOM decomposition (i.e., SOM qualities) may affect WEOM values (Table 2.4).

Table 2.4: Water-extractable organic matter (WEOM) from several SOM materials incubated for 60 days under aerobic laboratory conditions. †

Soil organic matter nature	WEOM
	mg C g^{-1}
Fresh maple leaves	260
Old maple leaves	21
Sphagnum moss	6
Fibric peat	3
Humic peat	2

† Information adapted from Moore (1998).

As for solid SOM, a wide range of molecules from labile (e.g., sugars, amino acids, organic acids, free amino acids, and amino sugars) to recalcitrant (e.g., heterocyclic-N, hydrophobic N compounds, and humified substances) have been identified in WEOM (Murphy et al., 2000). Nevertheless, WEOM appears to be the immediate organic substrate for soil microorganisms (Moore, 1998). The mobility of WEOM increases its importance related to soil N and C nutrient cycling processes.

2.2 Implications of Soil Organic Matter Qualities in Soil N and C Cycling Processes

The relative role that SOM qualities play compared to other soil parameters determining soil nutrient mineralization is not clear because SOM characteristics are rarely measured directly. So far, I demonstrated that SOM is a heterogeneous mixture of numerous compounds and molecules that can be extracted and/or fractionated into fractions using different approaches and techniques. Soil organic matter is fractionated into pools and/or fractions to examine the roles and implications to soil nutrient cycling processes. In Arctic ecosystems, where the growing season is short and soil nutrient availability is very low, SOM qualities – especially the labile SOM – may well be a major predictor of both soil nutrient mineralization and soil nutrient losses through

soil GHG emissions. Results from Grogan et al. (2001) and Grogan and Jonasson (2005) suggested that soil CO_2 emissions were mainly derived from recently fixed C such as fresh litter (e.g., LF) and rhizosphere exudates (e.g., WEOM). Similarly, a study from Greenland suggested that the allocation of recently fixed C by plants affected SOM qualities and then positively influenced soil CH_4 emissions. Unfortunately, no study from the Arctic has examined the effect of SOM qualities on soil N_2O emissions. However, a study from Brazil demonstrated that some labile SOM compounds (e.g., Carbohydrates-C) enhanced soil N_2O emissions (Garcia-Montiel et al., 2003).

2.2.1 Soil Organic Matter Density Fractions

The density fractionation technique of soil organic matter (SOM) has been widely used to separate fresh and decomposed SOM in almost all soil ecosystems because both LF and HF are physically and chemically different and are known to affect soil nutrient cycling processes (Cookson et al., 2005; Gregorich et al., 2006) such as N mineralization (Curtin and Wen, 1999; Hassink, 1995b; Sollins et al., 1984) and N immobilization (Ladd and Amato, 1980; Ladd et al., 1977). Therefore, fractions with a rapid turnover such as LF versus HF are generally assumed to play a dominant role in soil nutrient dynamics and cycling processes (Janzen et al., 1992). The labile character of the LF is important because of its large contribution to the plant-available N pool (Zech et al., 1997). Therefore, relating SOM characteristics, as determined by density fractionation with soil N and C cycling processes, will be useful to better understand the role of SOM qualities on soil nutrient cycling processes in the Arctic.

2.2.2 Solid-State ^{13}C NMR Spectroscopy

As shown above, the OAC group represents a fresh and partly decomposed C pool of SOM (Table 2.3). Therefore, OAC compounds are most likely related to fast-nutrient transformation processes (e.g., C/N mineralization and GHG emissions), whereas AC, AroC, and CbyC groups should be much more stable in time and represent the stabilized SOM. Moreover, C-group ratios such as OAC:AroC and OAC:AC, as determined by ^{13}C NMR spectroscopy, are good indicators of the overall quality of SOM (Baldock et al., 1992; Quideau et al., 2000). So far, only a few Arctic studies have characterized SOM using ^{13}C NMR spectroscopy (Dai et al., 2002;

Gundelwein et al., 2007) and none of them have related the results to soil C and N cycling rates. Relating SOM characteristics as determined by solid-state ^{13}C NMR spectroscopy with soil N and C cycling processes is full of promise from my perspective.

2.2.3 Water-Extractable Organic Matter

The WEOM appears to be an immediate organic substrate for soil microorganisms. Gross N mineralization decreased by 25% when water-soluble organic nitrogen (WSON) was removed from soil, which was attributed to WEOM being an easily-available SOM pool for heterotrophs (Cookson and Murphy, 2004). Modelling the movement of similar labile soil components (e.g., organic acids) showed that these soil components are only capable of migrating a few millimetres in soil due to rapid decomposition by soil microbes (Van Hees et al., 2005). Jones et al. (2004) found a half-life of approximately 6 minutes for amino acid extracted from WSON of grassland soils. A longer half-life of 72 minutes was found for WSON extracted over permafrost of taiga forest soils (Jones and Kielland, 2002). Therefore, labile pools of SOM such as WEOM (e.g., WSOC and WSON) potentially affect soil N mineralization processes in Arctic soils.

In the Arctic, the bioavailability of WEOM plays a large role in determining whether C is lost through leaching or lost as gaseous emissions following its decomposition by heterotrophic soil microbes (Gundelwein et al., 2007; Neff and Hooper, 2002). It has been shown that WEOM plays an important role in soil gas emissions and SOM C and N mineralization processes (Burford and Bremner, 1975; Hobbie et al., 2002; Neff and Hooper, 2002). For example, WEOM in soil has been strongly and positively correlated with soil denitrification capacities (Burford and Bremner, 1975). In Arctic ecosystems, Hobbie et al. (2002) observed a significant and positive association between WEOM and cumulative soil respiration (i.e., CO_2 production). The same pattern has been observed along the south to north Alaska transect by Neff and Hooper (2002) where a shrub tundra community exhibited the highest WEOM fluxes followed by tussock, spruce, and wet sedges. Therefore, relating SOM characteristics as determined by WEOM with soil N and C cycling processes will improve our understanding of the role of SOM characteristics on soil nutrient cycling processes in the Arctic.

2.3 Spatial and Landscape Considerations

In the Arctic, uplands are generally drier than depressions and vegetation tended to develop less easily on those dry landform units compared to mid-slopes, depressions, and lowlands. Consequently, Arctic landscapes are heterogeneous and can encompass a mosaic of wetland soils, riparian zones, well-drained lands, ridge-top stripes, and polar desert soils (Walker, 2000). Therefore, considering this heterogeneity of landscapes is essential when Arctic SOM is studied at the landscape scale.

At the landscape scale, topography plays an important role by affecting soil moisture, soil C and N cycling rates, and microclimates. In order to understand soil nutrient cycling processes at the landscape scale, landform segmentation can be used to divide landscapes into functionally distinct groups (Pennock and Corre, 2001). On a landscape basis, the largest C pool (i.e., highest SOM content) is often measured in depressions and poorly drained soils (Ping et al., 1997), where high moss abundance, low oxygen, and cold temperatures are combined (Hobbie et al., 2000). Depressions and poorly drained soils tend to accumulate more SOM than upper and well-drained soils because redistribution of water-soluble soil nutrients from upper slopes to depressions and creates more suitable conditions for soil microbial biomass and plant growth (Fahnestock et al., 2000; Giblin et al., 1991; Schimel et al., 1985). In the High-Arctic, soil CO_2 emissions have been shown to increase along a moisture gradient from a very dry and sparsely-vegetated heath to a densely-vegetated riverbed system (Sjögersten et al., 2006). In a Sub-Alpine ecosystem, Pacific et al. (2008) estimated that riparian zones emitted 57% more CO_2 than hillslope zones. Biasi et al. (2005) found larger N pools and higher N mineralization rates in inter-hummock areas where the soils were wetter and cooler compared with hummocks. The authors attributed this difference to the plant cover (i.e., differences in substrate qualities) where dry and warm hummock sites had grasses and sedges and the wet and cold inter-hummock had mosses and deciduous shrubs. In the literature, soils with contrasting topography were also reported to have different CH_4 and N_2O emissions. For example, a study from Churchill showed that marsh, ponds, and wet fen produced large CH_4 emissions compared to other drier ecosystems (Rouse et al., 1995). In High Arctic (i.e., Truelove), Chapin (1996) found higher nitrification (i.e., NO_3^- production) and denitrification (i.e., N_2O production) rates in willow-herb

hummock compared to sedge meadow. More recently, Ma et al. (2007) concluded that nitrifier denitrification was the dominant process that produce N_2O from Truelove soils and mostly occurred in the wettest areas of the landscape. These results showed the strong influence of topographic gradient of soil moisture on C and N cycling processes. Therefore, understanding the effect of topography across Arctic landscapes is important for assessing climate change impacts on soil C and N cycling processes such as N mineralization and GHG emissions. Furthermore, because plant redistribution at the landscape scale is strongly dependent on topography (Giblin et al., 1991), considering topography is also recommended when SOM characteristics are studied at the landscape scale.

2.4 Conclusions

Arctic soils store a great amount of SOM (about 25% of the world's C). However, relatively little is known about SOM characteristics nor how qualities vary across the Arctic and across landscapes. In addition, even less is known about how SOM characteristics may ultimately influence key soil N and C cycling processes such as N mineralization, CO_2, CH_4, and N_2O emissions. This literature review showed that combining density fraction technique, solid-state ^{13}C NMR spectroscopy, and water-extractable organic matter is a suitable approach for characterizing fresh and labile Arctic SOM involving N and C cycling processes. The following main research chapters will characterize the properties of SOM (i.e., SOM characteristics) of three distinct Arctic ecosystems, verify how some key N and C cycling processes vary across Arctic ecosystems and landscapes, and investigates how SOM qualities may ultimately affect our measured key N and C cycling processes at the landscape scale.

Chapter 3 : Soil Organic Matter Qualities of three Arctic Ecosystems

Preface

Arctic soils store large amounts of SOM and relatively little is known about SOM qualities nor how qualities varies across the Arctic and across landscapes. In addition, even less is known about how SOM qualities may ultimately influence key soil N and C cycling processes such as N mineralization, CO_2, CH_4, and N_2O emissions. This chapter represents a first investigation of the soil organic matter characteristics found in Arctic soils. Findings and gathered data from this chapter are used (Chapter 5) to determine the influence of SOM qualities on C and N cycling processes.

3.1 Abstract

Cryosolic soils store large amounts of carbon (C) because soil organic matter (SOM) decomposition is slower than plant growth. The response of Arctic SOM to climate change is likely to depend not only on temperature, but upon complex interactions between soil properties and SOM chemistry as well. The study objectives were to assess the SOM qualities from Arctic surface soils and determine how Arctic SOM characteristics differ: 1) between mineral (<17% carbon) and organic surface soils (>17% carbon); and 2) among three Arctic ecosystems (i.e., Sub-, Low-, and High-Arctic). This study was conducted in three Arctic ecosystems: Sub-Arctic (Churchill, MB; n=138), Low-Arctic (Daring Lake, NWT; n=60), and High-Arctic (Truelove Lowlands, NU; n=54). The 0 to 10 cm depth of several different Cryosolic soils were sampled. The results from density fractionation and solid-state CPMAS ^{13}C nuclear magnetic resonance (NMR) spectroscopy showed that organic surface soils contained relatively more labile C than mineral surface soils. Organic soils contained about 13% more O-Alkyl-C and 30% less Aromatic-C than mineral soils. Furthermore, for Churchill, Daring Lake, and Truelove organic soils, 53, 73, and 20% of the C was included in the light fraction of SOM [LF (LF<1.55 g mL^{-1})] whereas 24, 19, and 14% of the C was included in the LF of mineral soils, respectively. Organic surface soils of Sub- and Low-Arctic ecosystems contained relatively more labile C than High-Arctic. Results showed that Sub-Arctic and Low-Arctic ecosystems store about 15% more O-alkyl-C and 35% less Aromatic-C than High-Arctic organic soils. The results suggest greater inputs of fresh plant residues with higher C:N ratios in Sub- and Low-Arctic compared to High-Arctic. Organic surface soils from Sub- and Low-Arctic soil have a high release potential under more suitable conditions for heterotrophic soil microbes such as warmer and wetter climates. The combination of large soil C stocks, high SOM lability, and severe climate change may well result in a release of greenhouse gases into the atmosphere. However, cryoturbation and soil moisture redistribution need to be considered because these processes directly and indirectly affect soil C storage as well as soil nutrient availability of Arctic soils.

3.2 Introduction

Cryosolic soils, the dominant soil in the Arctic, store large amounts of carbon (C) because soil organic matter (SOM) decomposition has historically been slower than plant growth (Weintraub and Schimel, 2005). These permafrost-affected soils store approximately 25% of the world's organic C which represents 61% of the C in all soils of North America (Tarnocai et al., 2008). An estimated 63% of the C of permafrost-affected soils is stored above the permafrost table in the active layer (Ping et al., 2008). Future environmental changes such as temperature and precipitation increases (Huntington et al., 2005; Kattsov et al., 2005) will determine whether Arctic soils will continue to accumulate SOM (i.e., net sink), or instead become an source of greenhouse gases (GHG) via SOM decomposition (i.e., net source).

The response of Arctic soils to climate change is likely to depend not only on temperature increase, but upon complex interactions between soil properties and SOM chemistry. Soil organic matter includes a wide range of organic materials from labile (e.g., fresh vascular plant residues) to recalcitrant (e.g., ester and lignified molecules) components which slowly accumulate over thousands of years (Paul et al., 2001; Trumbore, 1993). In soil, there are two phases of SOM: 1) soluble SOM known as water-extractable organic matter (WEOM) and 2) solid SOM. Water-extractable organic matter is defined operationally as soil fraction (<0.45 μm) included in water. Although WEOM concentrations in the soil are generally low, the mobility and lability of this fraction increase its importance in nutrient cycling (Chantigny et al., 2008). For example, WEOM contributes to soil acidity, pollutant toxicity, nutrient mobility and availability, and provides energy for heterotrophic soil microbes (Chantigny, 2003; Moore, 1998; Zsolnay, 1996). Solid SOM is defined as the fraction of the soil (<2mm) that includes a wide range of compounds such as plant, animal, and microbial residues (cells, tissues, and metabolites) at various stages of decomposition. In Arctic soils, SOM affects many processes related to soil nutrient cycling. For example, Grogan et al. (2001) showed that soil respiration derived from fresh litter residues was the principal source of CO_2 efflux. More recently, Buckeridge et al. (2010b) found that soils with the greatest quantity and highest lability of SOM had both the most rapid N cycling and produced the tallest vegetation (i.e., tall shrubs). Furthermore, Ping et al. (1998) indicated that high carbohydrate concentrations found in Alaskan

Arctic soils (i.e., 2 to 3 times greater than southern soils) were relatively easily decomposed and were the ideal substrates for CH_4 production. Therefore, the most labile compounds of SOM are dominant controls on soil nutrient processes such as GHG production and N mineralization.

In the Arctic, surface soil (i.e., upper soil horizons) properties and conditions are especially important because they support the biological component of the system and therefore exert a strong control on the vegetation patterns across the landscape (Michaelson et al., 2008). Differentiating between mineral and organic soil horizons is crucial for assessing the fate of surface soils because mineral and organic surface soils do not experience similar chemical, biological, and physical processes (Nowinski et al., 2010; Uhlirova et al., 2007). For example, Kramer et al. (2004) found that organic surface horizons in Alaska contained relatively more labile materials (e.g., high O-Alkyl-C content) than mineral horizons. An *in situ* warming experiment in Antarctica showed that warming increases SOM C and N contents in organic soil horizons to a greater extent than in mineral soil horizons (Day et al., 2008). Furthermore, the reduced vegetation cover on mineral surface soils ensures a high heat flux and a relatively deep active layer whereas the relatively thick organic surface soils insulate the soil, resulting in creating a shallower active layer. Relatively little is known about SOM qualities nor how qualities vary across the Arctic. **The study objectives were to assess the SOM characteristics from Arctic surface soils and determine how Arctic SOM characteristics differs: 1) between mineral and organic surface soils; and 2) among three Arctic ecosystems (i.e., Sub, Low, and High-Arctic.**

3.3 Material and Methods

3.3.1 Sampling Locations

This study was conducted in three distinct Arctic ecosystems: Sub-Arctic (Churchill, MB), Low-Arctic (Daring Lake, NWT), and High-Arctic (Truelove, NU) (Figure 3.1). Daring Lake and Truelove were sampled in 2008 and Churchill was sampled in 2009. To capture within-ecosystem variations, the sampling locations were distributed among several dominant soil types (Table 4.1). All three ecosystems were sampled near the end of their growing season, from two to three weeks before plant senescence.

Figure 3.1: Ecosystem and site locations investigated for this study: Sub-Arctic (Churchill, MB), Low-Arctic (Daring Lake, NWT), and High-Arctic (Truelove, NU).

Table 3.1: Dominant soil classification and vegetation sampled for this study.

Ecosystem Location	Number of Samples	Dominant Soil Type †	Dominant Vegetation	Surface Soil‡	
				Mineral	Organic
Sub-Arctic					
Churchill, MB (58° 45'N; 93° 51'W)					
	12	Brunisolic Eutric Static Cryosol	Lichens	12	
	12	Histic Regosolic Static Cryosol	Shrubs	2	10
	12	Gleysolic Turbic Cryosol	Bryophyte & Shrubs		12
	24	Regosolic Static Cryosol	Lichens	24	
	12	Cumulic Regosolic Static Cryosol	Lichens & Shrubs	7	5
	12	Cumulic Gleysolic Static Cryosol	Bryophytes & Graminoids		12
	12	Histic Eutric Static Cryosol	Shrubs	12	
	12	Gleysolic Static Cryosol	Bryophytes & Graminoids	8	4
	15	Regosolic Turbic Cryosol	Shrubs		15
	15	Histic Regosolic Turbic Cryosol	Lichens		15
Low-Arctic					
Daring Lake, NWT (64^{o}E 50'N; 111^{o}E 38'W)					
	20	Orthic Dystric Static Cryosol	Lichens	20	
	20	Eluviated Brunisolic Dystric Static Cryosol	Shrubs & Lichens	18	2
	20	Histic Regosolic Turbic Cryosol	Bryophytes & Graminoids	9	11
High-Arctic					
Truelove, NU (75^{o}E 33'N; 84^{o}E 40'W)					
	10	Brunisolic Eutric Static Cryosol	Lichens	2	8
	10	Brunisolic Eutric Turbic Cryosol	Bryophytes & Lichens		10
	10	Gleysolic Turbic Cryosol	Bryophytes & Graminoids	5	5
	24	Fibric Organic Turbic Cryosol	Lichens, Bryophytes & Graminoids		24
Total	252			119	133

† Classified according to the Canadian System of Soil Classification (Soil Classification Working Group, 1998). ‡ Number of sample of mineral < 17% Soil Organic Carbon < organic surface soils.

3.3.1.1 Sub-Arctic: Churchill

The Churchill ecosystem is located in Manitoba, Canada (58° 45'N; 93° 51'W). All sites sampled for this study were located within the tundra vegetation zone between 1 and 5 km from the shores of Hudson Bay. The Precambrian Shield, which underlies the entire coastal region, was buried by the younger Ordovician and Silurian limestones and dolomites deposited during the most recent glaciations (8000 B.P.). The area is characterized by raised beaches formed during the regression of the postglacial Tyrrell Sea and by isostatic rebound (Dredge, 1992). On boggy wetlands and where winter temperatures are harsh and snow cover is thin, hummocks have developed. The Churchill climate is classified as Arctic continental with a mean temperature of -7.5 °C and a mean annual precipitation of 412 mm (Lafleur et al., 2001). Between 1996 and 2006, a permanent weather station measured a mean annual temperature of -5.8 ± 1.6 °C (mean ± standard deviation) and a mean annual precipitation of 501.2 ± 89.1 mm (Environment Canada, 2011). The growing season typically occurs from early June to late August with an average daily maximum of 9.7 °C (Lafleur et al., 2001). The region is underlain by continuous permafrost of about 80 m thickness (Dredge, 1992). Static and Turbic Cryosols were sampled across the range of local parent materials, including fluvial and marine (Table 3.1).

3.3.1.2 Low-Arctic: Daring Lake

The Daring Lake ecosystem is located in the North West Territories, Canada (64^{o}E 50'N; 111^{o}E 38'W) 70 km north of the tree-line and approximately 300 km northeast of Yellowknife, Canada. Exposed bedrocks and lakes account for a large proportion (i.e., ≈ 50%) of the landscape. The area is characterized by complex esker systems which are mainly composed of sandy till materials with evidence of soil mass movement (Dredge et al., 1999; Rampton, 2000), and localized deposits of fine-grained materials (e.g., silty sand to clayey silt) and peat (Dredge et al., 1999). The entire region is underlain by a thick permafrost layer (>160 m) with the summer active-layer depths ranging from 15 to 120 cm depending on regional parameters such as vegetation cover, soil materials, and soil moisture (Dredge et al., 1999). Seven-year climate records from a permanent weather station indicated a mean annual air temperature of -9.0 °C (Nobrega and Grogan, 2008). No precipitation data are shown for this site because when and

how data were collected cannot be clearly answered and/or verified. Static and Turbic Cryosols were sampled across the range of local parent materials, including lacustrine and fluvial (Table 3.1).

3.3.1.3 High-Arctic: Truelove

The Truelove (75°E 33'N; 84°E 40'W) ecosystem is a polar oasis (≈43 km^2) situated on the northern coast of Devon Island (≈ 54,000 km^2), Nunavut, Canada. The geomorphic characteristics of the Pleistocene deposits of Truelove lowlands make it unique compared to the higher (300 m) and drier surrounding Cambrian age plateau. Similar to Churchill, the raised beach system at Truelove was formed during the Holocene by the retreat of the ice-cap (in this case the Devon ice-cap), progressive isostatic uplift, and wave as well as ice-push actions (Bliss, 1977; Lev and King, 1999). Therefore, the Precambrian metamorphic bedrocks of the lowlands are mantled with limestones and dolomites with a complex assemblage of fluvial, lacustrine, and periglacial deposits. Raised beaches shield the adjacent meadows from wind, increase meadow snow cover, and increase summer moisture by restricting lateral drainage (Svoboda, 1977). Therefore, this unique ecosystem has developed greater biological diversity than the surrounding plateau area of Devon Island (King, 1991). The entire coastal lowland region is underlain by a thick permafrost layer (>200m) (Brown, 1977). The climate data available for Truelove is very limited. Between 1970 and 1974, Truelove received mean annual precipitation of 185 mm, of which only 36 mm was rainfall (Rydén, 1977). Between 1996 and 2006 at Grise Fiord (~80 km north Truelove; 76°E 25'N; 82°E 54'W), a permanent weather station measured a mean annual temperature of -14.2 ± 1.0 °C (mean ± standard deviation) and a mean annual precipitation of 183.8 ± 34.2 mm (Environment Canada, 2011). Static and Turbic Cryosols were sampled across the range of local parent materials, including fluvial and organic (Table 3.1).

3.3.2 Method of Sampling

The soils sampled as well as the number of samples for each location differed between ecosystems (Table 3.1). A minimum sample spacing of 5 m was measured between sampling points. For each sampling point, the soil (0-10 cm) and associated vegetation (i.e., above and below ground materials) were gently cut with a soil knife (i.e., to keep the soil micro-sites as

intact as possible) and placed into plastic pot (Histoplex Histology Containers, 500ml). The 0-10 cm was selected because most of N and C cycling processes are strongly active in this section of the soil profile in the Arctic (Nadelhoffer et al., 1991). When stone rock content exceeded 10 % of the volume (visually determined), the soil was gently sieved to <4.75 mm. A sub-sample was used immediately for water-extractable organic matter (Section 3.3.4.3). All soil samples were stored frozen. In the laboratory, soils were thawed, the roots were removed, and the soils were sieved to <2 mm and then air-dried prior to analysis.

3.3.3 Soil General Analysis

Soil gravimetric water content (moisture) was calculated using oven weight loss (105°C for 24 h). Soil pH was measured in 0.01 *M* $CaCl_2$ (Hendershot et al., 2008) using a portable pH meter (model SP80 PC pH/cond, VWR International, Mississauga, ON). Soil organic carbon (SOC) and total nitrogen (TN) were determined by combustion using a carbon analyzer (model C632, Leco Corporation, St. Joseph, MI) and a CNS analyzer (model Leco-2000, Leco Corporation, St. Joseph, MI), respectively. To remove inorganic C, all samples were acid-treated with 6% H_2SO_3 prior to analysis (Skjemstad and Baldock, 2008). For each sampling point, the soil was classified as either mineral or organic based on its SOC content (i.e., Mineral < 17% SOC < Organic) (Soil Classification Working Group, 1998).

3.3.4 Soil Organic Matter Characteristics

3.3.4.1 Soil Organic Matter Density Fractions

The SOM density fractionation technique was used to separate light fraction (LF) from heavy fraction (HF) of SOM (Gregorich and Beare, 2008). Approximately 20 mL of air-dried and 2 mm-sieved soil (i.e., ≈17g of mineral soil and ≈5 g of organic soil) were shaken (200 rpm for 1 h) in 100 mL of NaI solution with a specific density adjusted to 1.55 g mL^{-1} (Paré and Bedard-Haughn, 2011). After shaking, the samples were covered to prevent density change in the NaI solution and stored at ambient laboratory conditions for 48 h. Thereafter, the floating LF was collected using a vacuum system and filtered through a 0.45 µm membrane (Millipore Corporation, Billerica, MA). A second density fractionation cycle (as above) was performed to

ensure a complete separation of the LF from the HF. Thereafter, both LF and HF fractions were i) washed in 100 mL of 0.01 *M* $CaCl_2$ solution and 100 mL of de-ionized water, ii) dried (60 °C for 48 h), and iii) ground (<420 μm) prior to analysis. Organic C and total N of each SOM fraction (C-LF, C-HF, N-LF, and N-HF) were determined as above. In order to remove carbonates, all HF samples were acid-treated with 6% H_2SO_3 prior to organic C determination (Skjemstad and Baldock, 2008).

3.3.4.2 Solid-State CPMAS ^{13}C NMR

Solid-state CPMAS ^{13}C Nuclear Magnetic Resonance (NMR) spectroscopy was used to characterize the chemical structures of the SOM (Simpson and Preston, 2008). All analyses were carried out at the Canada Plant Biotechnology Institute in Saskatoon. Solid-state NMR spectra were acquired on a Bruker DRX-400 NMR spectrometer (Bruker BioSpin Ltd, Milton, ON) (B_0 = 8.46 T; $\nu_L(^1H)$ = 360.119 MHz; $\nu_L(^{13}C)$ = 90.563 MHz). A 7 mm double-resonance magic-angle spinning (MAS) probe was used. The magic angle was set by observing the ^{79}Br free-induction decay signal and maximizing the number of rotational echoes for solid KBr while using a spinning rate of 2.3 kHz. Chemical shift referencing and ^1H pulse width calibration were carried out using a solid sample of adamantane with a spinning rate of 2.3 kHz. The chemical shift of the high frequency ^{13}C NMR signal for adamantane was set to 38.56 ppm and a ^1H π /2 pulse width of 5.0 ms was found.

All soil samples were examined under identical experimental conditions. Samples were packed into 7 mm (o.d.) zirconia rotors and spun at a frequency of 5.0 kHz. A $^1H \rightarrow {}^{13}C$ cross-polarization pulse sequence was used to acquire data using a spectral width of 300 ppm, acquisition time of 18.96 ms, contact time of 1.0 μs, ^1H $\pi/2$ proton pulse width of 5.0 μs, and pulse delay of 1 s. A total of 6144 acquisitions were summed for each soil sample and data were processed using an exponential multiplication factor of 30 Hz. Bruker Topspin 1.3 software (Bruker BioSpin Ltd, Milton, ON) was used to determine the relative amounts of various functional groups present in the soil samples by chemical shift regions or spectra ranges (Table 3.2, Appendix B).

Table 3.2: Spectra ranges, region names, and chemical content of soil organic matter determined by solid-state ^{13}C NMR spectroscopy. †

Spectra range, ppm	Region name	Chemical content
0-45	Alkyl-C (AC)	Lipids Fatty acids Plant polymers
45-110	O-alkyl-C (OAC)	Cellulose, Hemicelluloses Methoxyl-C (45-60 ppm) Proteins Carbohydrates (CC) (60-94 ppm) Side chains of lignin and protein
110-160	Aromatic-C (AroC)	Lignin derived molecules Protein derived molecules
160-220	Carbonyl-C (CbyC)	Esters Carboxyl groups Amide Carbonyls

† Information adapted from Helfrich et al. (2006), Simpson and Preston (2008), and Blumfield et al. (2004).

3.3.4.3 Water-Extractable Organic Matter

Approximately 10 g of fresh soil was gently mixed with 100 mL of water to determine the soil water-extractable organic matter (WEOM) (Chantigny et al., 2008). All samples were extracted on site, *in situ* incubated for 24 h, hand shaken, and filtered through 0.4 µm polycarbonate membrane filter (Whatman Inc., Piscataway, NJ) following the protocol of Chantigny et al. (2008). Filtered extracts were stored frozen until analysis.

Water-soluble organic C (WSOC, mg kg^{-1} soil) and total N (WSN, mg kg^{-1} soil) concentrations in the filtered extract were determined simultaneously by oxidation and chemiluminescence measurement methods (TOC-V and TNM-1 Measurement Unit, Shimadzu Scientific Instruments, Kyoto, Japan). Ammonium concentrations (NH_4^+, mg kg^{-1} soil) were determined colorimetrically following the phenolhypochlorite method (Solorzano, 1969) using a SmartChem 200 Discrete Autoanalyzer (Westco Scientific, Brookfield, CT). Nitrate concentrations (NO_3^-, mg kg^{-1} soil) were determined by reducing NO_3^- to nitrite (NO_2^-) by passage through an open tubular copperized cadmium redactor. Nitrite concentrations were then determined colorimetrically by diazotizing with sulphanilamide followed by coupling with N-(naphthyl)-ethylenediamine dihydrochloride using the SmartChem 200 Discrete Autoanalyzer. Water-soluble organic nitrogen (WSON, mg kg^{-1} soil) was calculated according to equation 4.1.

$$\mathrm{WSON} = \mathrm{WSN} - ([\mathrm{NH_4^+}] + [\mathrm{NO_3^-}]) \qquad (3.1)$$

3.3.5 Statistical Analysis

Variance homogeneity was evaluated with the Levene test. Data were transformed (i.e., logarithm or exponential) when they were not normally distributed. Multiple-factors ANOVA (type III of squares) was used to determine differences in soil properties and SOM quality parameters between ecosystems and soil type using general linear model procedure in SPSS version 13 for Windows (SPSS Inc., 2004). Correlations among SOM quality parameters were examined using the Pearson correlation procedure in SPSS.

3.4 Results and Discussion

3.4.1 Soil Organic Matter Density Fractions

The C and N measured in the LF and HF of SOM were higher in organic soils than in mineral soils (Table 3.3). Churchill and Daring Lake organic soils had more C and N stored in LF of SOM than Truelove (Table 3.3). This may be explained by the difference of vegetation between ecosystems where Churchill and Daring Lake (i.e., Sub- and Low-Arctic) organic soils had greater above-ground biomass (e.g., tall shrubs) than Truelove (i.e., High-Arctic). Low and similar C-LF and N-LF values were measured for all mineral surface soils (Table 3.3) because the vegetation on mineral soils (e.g., dry heath lichens) was similar among ecosystems. Organic soils from all three ecosystems had different C-HF and N-HF values, suggesting different N cycling processes among these ecosystems (Accoe et al., 2004; Curtin and Wen, 1999; Hassink, 1995a). For both types of surface soils (i.e., mineral and organic), Truelove had the lowest LF C:N and HF C:N values most likely because Churchill and Daring Lake (i.e., Sub- and Low-Arctic) had more lignin-rich plants than Truelove (i.e., High-Arctic). Small trees (e.g., *Picea glauca*) and shrubs (e.g., *Vaccinium uliginosum*) characterized vegetation at Churchill and Daring Lake, whereas herbaceous plants (e.g., *Dryas integrifolia*) characterized vegetation at Truelove.

When compared with the values reported in the comprehensive review of LF and HF literature by Gregorich et al. (2006), I found that the LF C:N values were ~50% higher for Churchill and Daring Lake and ~25% higher for Truelove compared with agricultural, forest, and grassland soils. The results from Churchill and Daring Lake corresponded to those found for the southern part of Siberia (Gundelwein et al., 2007). However, comparisons among studies and ecosystems are problematic because of the differences in density of the heavy liquid used to separate LF and HF. Recently, Paré and Bedard-Haughn (2011) determined an optimum liquid density of 1.55 g cm^{-3} to separate LF and HF of SOM from few Canadian Arctic ecosystems. The data that supported the reasoning are attached to this document (Appendix A). Liquid density of 1.55 g cm^{-3} may serve as a reference starting point to separate LF and HF from Arctic SOM.

Table 3.3: Statistical comparisons of organic matter quality parameters among ecosystems (E) and between soil type (S). †

	Churchill	Daring	Truelove	Churchill	Daring	Truelove	ANOVA		
	---------- Mineral ----------			---------- Organic ----------			E	S	E x S
Soil Properties							*P*	*P*	*P*
Moisture §, g g^{-1}	0.5(0.6)^{b}	0.6(0.3)^{a}	0.8(0.5)^{a}	2.8(1.4)^{a}	3.2(1.1)^{a}	1.4(1.1)^{b}	0.007	<0.001	<0.001
pH	6.5(0.2)^{a}	4.0(0.4)^{b}	6.5(0.1)^{a}	5.8(1.0)^{b}	3.3(0.1)^{c}	6.1(0.4)^{a}	<0.001	<0.001	0.352
SOC ¶, g $100g^{-1}$	7.6(4.2)^{a}	4.9(3.5)^{b}	11.7(4.9)^{a}	40.3(7.2)^{a}	40.0(6.2)^{a}	29.3(5.4)^{b}	<0.001	<0.001	<0.001
TN §, g $100g^{-1}$	0.4(0.2)^{b}	0.2(0.2)^{c}	0.9(0.4)^{a}	2.1(0.7)^{a}	1.4(0.2)^{b}	1.9(0.2)^{a}	<0.001	<0.001	<0.001
Soil C:N §	20.2(6.3)^{b}	25.9(8.3)^{a}	14.7(2.6)^{c}	22.2(10.6)^{b}	29.3(3.4)^{a}	15.1(2.3)^{c}	<0.001	0.122	0.723
Density Fractions									
C-LF §, g $100g^{-1}$	1.8(1.4)^{a}	0.9(1.3)^{b}	1.6(2.9)^{ab}	21.1(10.7)^{b}	30.0(7.9)^{a}	5.9(6.0)^{c}	<0.001	<0.001	<0.001
C-HF ¶, g $100g^{-1}$	5.4(3.8)^{b}	4.4(2.5)^{b}	12.0(4.4)^{a}	17.0(6.0)^{b}	9.4(3.4)^{c}	22.1(3.3)^{a}	<0.001	<0.001	<0.001
N-LF ¶, g $100g^{-1}$	0.07(0.06)^{a}	0.03(0.04)^{b}	0.08(0.15)^{ab}	0.87(0.54)^{a}	0.97(0.24)^{a}	0.31(0.28)^{b}	<0.001	<0.001	<0.001
N-HF ¶, g $100g^{-1}$	0.23(0.18)^{b}	0.22(0.13)^{b}	0.86(0.37)^{a}	1.02(0.53)^{b}	0.34(0.15)^{c}	1.59(0.31)^{a}	<0.001	<0.001	<0.001
LF C:N ¶	27.2(5.0)^{b}	31.6(6.1)^{a}	22.9(4.1)^{b}	27.2(10.4)^{b}	31.1(3.9)^{a}	18.6(2.6)^{c}	<0.001	0.075	0.266
HF C:N §	25.6(8.4)^{a}	21.2(4.7)^{b}	15.2(3.5)^{c}	19.7(8.3)^{b}	28.5(4.4)^{a}	14.2(1.9)^{c}	<0.001	0.795	<0.001
Solid-state ^{13}C NMR Spectroscopy									
Carbonyl-C (CbyC) §, %	9.3(2.5)^{a}	10.3(6.3)^{a}	9.5(4.8)^{a}	6.9(1.2)^{b}	4.5(1.0)^{c}	8.2(1.6)^{a}	<0.001	<0.001	<0.001
Alkyl-C (AC), %	20.1(2.6)^{b}	26.1(4.3)^{a}	20.3(4.9)^{b}	19.3(1.9)^{b}	23.2(3.2)^{a}	22.7(4.3)^{a}	<0.001	0.494	0.008
Aromatic-C (AroC) §, %	11.7(3.9)^{b}	15.3(4.6)^{a}	17.7(7.0)^{a}	8.6(1.5)^{b}	7.0(1.6)^{c}	12.7(2.3)^{a}	<0.001	<0.001	<0.001
O-Alkyl-C (OAC) ¶, %	58.8(5.0)^{a}	48.3(7.5)^{b}	52.6(6.7)^{ab}	65.2(2.9)^{a}	65.3(4.0)^{a}	56.4(3.4)^{b}	<0.001	<0.001	<0.001
Carbohydrates-C (CC), %	42.3(4.8)^{a}	33.2(5.6)^{b}	33.8(4.5)^{b}	47.5(3.0)^{a}	48.5(3.8)^{a}	37.7(3.5)^{b}	<0.001	<0.001	<0.001
CC:MC §	5.4(1.4)^{a}	4.6(1.1)^{b}	3.6(1.1)^{c}	6.6(1.5)^{a}	7.6(1.8)^{a}	4.0(1.2)^{b}	<0.001	<0.001	<0.001
OAC:AroC §	5.8(2.8)^{a}	3.5(1.4)^{b}	3.4(1.3)^{b}	7.8(1.6)^{a}	10.0(3.3)^{a}	4.6(1.0)^{b}	<0.001	<0.001	<0.001
OAC:AC §	3.0(0.5)^{a}	1.9(0.4)^{b}	2.7(0.4)^{a}	3.4(0.5)^{a}	2.9(0.5)^{b}	2.6(0.7)^{b}	<0.001	<0.001	<0.001
Water-Extractable Organic Matter (WEOM)									
WSOC ¶, µg g^{-1}	38.5(36.0)^{a}	48.2(46.7)^{a}	60.3(37.8)^{a}	175.4(143.2)^{b}	622.8(257.7)^{a}	198.4(160.4)^{b}	<0.001	<0.001	<0.001
WSON ¶, µg g^{-1}	0.9(1.6)^{b}	1.1(1.0)^{b}	2.8(1.4)^{a}	2.4(7.3)^{b}	10.1(4.6)^{a}	10.3(8.4)^{a}	<0.001	<0.001	0.031
WEOM C:N ¶	17.9(4.7)^{b}	57.7(18.3)^{a}	20.6(6.4)^{b}	20.2(3.4)^{b}	70.0(16.0)^{a}	17.4(4.6)^{b}	<0.001	0.117	0.011
n	65	47	7	73	13	47			

Mean(standard deviation). †Multiple-factors ANOVAs (type III of squares) among ecosystems and soil types. Ecosystem (df=2): Sub-Arctic (Churchill), Low-Arctic (Daring Lake), and High-Arctic (Truelove). Soil Type (df=1): mineral (<17% carbon) and organic (>17% carbon). Logarithm (§) or exponential (¶) transformations applied to meet normality. Ecosystems not sharing a letter (per soil type) are different at $P<0.05$ using Games-Howell as a post hoc test (equal variances not assumed). As shown on Table 3.2, CC are a subset of OAC (CbyC+AC+AroC+OAC=100%). Light fraction (LF<1.55 g mL^{-1}) and Heavy fraction (HF>1.55 g mL^{-1}) of soil organic matter. WSOC: Water-soluble organic carbon. WSON: Water-soluble organic nitrogen.

3.4.2 Solid-State CPMAS ^{13}C NMR

The proportion of labile C (e.g., OAC and CC) was significantly higher in organic than mineral surface soils (Table 3.3). Furthermore, mineral surface soils had relatively more recalcitrant C (e.g., CbyC; AC; and AroC) than organic surface soils (Table 3.3). Most literature has consistently demonstrated that the preferred materials for decomposition by soil microbes are in the OAC group because this group is generally dominated by celluloses and other polysaccharides (e.g., carbohydrates-C); whereas AC, AroC, and CbyC groups tend to decompose slowly over time (Lützow et al., 2006; Skjemstad et al., 1997; Sollins et al., 1996). Therefore, C-group ratios such as OAC:AroC and OAC:AC are good indicators of the overall characteristics of SOM since soil microorganisms preferably degrade OAC group in most of natural ecosystems such as oak, pine, and mixed forests, and northern uncultivated organic soils from Québec (Baldock et al., 1992; Quideau et al., 2000). Organic soils had significantly higher 'lability' ratios (e.g., CC:MC; OAC:AroC; and OAC:AC), suggesting that the organic soils were more labile than mineral soils (Table 3.3). These results support and reinforce the previous SOM density fraction findings.

Churchill mineral surface soils store relatively more labile C (e.g., higher CC:MC and OAC:AroC ratios) than Daring Lake or Truelove mineral surface soils (Table 3.3). Churchill and Daring Lake organic soils had more labile C than Truelove organic soils (Table 3.3). This may be explained by the difference of vegetation between ecosystems where Churchill and Daring Lake (i.e., Sub- and Low-Arctic) organic soils had higher above-ground biomass (e.g., tall shrubs) than Truelove (i.e., High-Arctic). Therefore, this condition contributed to greater accumulation of fresh and labile SOC in the Churchill and Daring Lake organic surface soils compared to Truelove.

Compared with other natural ecosystems, both organic and mineral soils had ~20% more OAC and ~20% less AC than a northern hardwood forest soil from New Hampshire, USA (Ussiri and Johnson, 2003) and ~20% more OAC and ~5% less AC than two Prairie soils (Baldock et al., 1992). Similarly, our Arctic soils had ~10% more OAC and 10% less AC than a spruce forest of Bavaria, Germany (Helfrich et al., 2006). For our Arctic surface soils, CC represented 33 to 48% of the total C pool, which was approximately 70% of the entire OAC group. Similarly, Strebel et

al. (2010) recently found that the CC concentrations represented approximately 40% of the C pool of a High-Arctic site in Svalbard, Norway. Therefore, high proportions of OAC and CC and small proportions of AC, AroC, and CbyC of Arctic surface soils indicated a small degree of humification of SOM from Arctic surface soils. Low temperatures, permafrost table and its interaction with soil hydrology are soil conditions that reduce SOM decomposition (Hobbie et al., 2000; Tarnocai et al., 2008) and hence, explain the smaller degree of humification of SOM from Arctic surface soils compared to soils of more temperate ecosystems.

3.4.3 Water-Extractable Organic Matter

The C and N measured in WSOC and WSON were significantly higher in organic than in mineral surface soils (Table 3.3) because soils with higher SOC generally have higher WSOC and WSON pools (Chantigny, 2003; Zsolnay, 1996). The WEOM C:N values did not differ between mineral and organic soils (Table 3.3), suggesting that the WEOM characteristics were similar between both types of soil. For mineral surface soils, WSOC values did not significantly differ among ecosystems whereas WSON values were slightly higher for Truelove (Table 3.3). Daring Lake organic soils had significantly higher WSOC than Churchill and Truelove organic soils (Table 3.3). Higher plant biomass, and hence higher SOC content, found in Churchill and Daring Lake compared to Truelove (Table 3.3) could not explain this difference. Other hypotheses can be suggested. First, differences in WEOM among sites could be simply caused by temporal variations, since WEOM can vary considerably among seasons and years (Zsolnay, 2003). However, because Daring Lake had approximately 3-fold higher WSOC than Churchill and Truelove, I believe that this great difference could not be caused only by temporal variations. Second, low soil pH measured in Daring Lake compared to Churchill and Truelove (Table 3.3) may promote dissolution of SOC since most of SOC solubility is pH-dependent (Anderson and Schoenau, 2008; Swift, 1996). Hypothetically, significantly lower soil pH found in Daring Lake could drive to a different soil WSOC steady state. However, higher soil WEOM values measured at near-neutral pH (pH 7.4) compared to acid soils (pH 4.5-5.3) do not support this hypothesis (Kuiters and Mulder, 1993). Third, it is possible that plant roots from Daring Lake released more water-soluble organic compounds since plants can directly increase soil WSOC by releasing C into soil solution (Séguin et al., 2004). Plants from Daring Lake might have some advantages to

do so because this ecosystem appears to be the most N limited, as reflected by the lowest TN and the highest soil C:N values (Table 3.3). Churchill and Truelove mineral and organic soils had lower WEOM C:N values than Daring Lake (Table 3.3). The parent soil material may explain this phenomenon. Churchill and Truelove soils were both formed on carbonate-rich parent materials whereas Daring Lake soil was formed on acidic parent materials – reflected by soil pH values (Table 3.3). Soils close to neutrality, such as Churchill and Truelove soils, tend to have a more active diverse soil microbial community than acidic soils (Anderson and Joergensen, 1997; Neale et al., 1997; Persson et al., 1989), such as found in Daring Lake, contributing to higher WEOM C:N ratios in acidic mineral and organic soils. The results from WEOM were also consistent with other SOM quality parameters where Daring Lake organic soils had also the highest soil C:N, LF C:N, HF C:N, CC:MC, and OAC:AroC values (Table 3.3). Therefore, Daring Lake organic soils store relatively fresher and less-humified (i.e., labile) SOM compared to Churchill and Truelove.

The WSOC values were approximately 10-fold lower compared to most of more temperate forest surface soils (Chantigny, 2003; Zsolnay, 1996). Furthermore, the WEOM C:N ratios were about 4-fold higher than those measured during many years of forest-stand experimentation from northern Alberta (Teklay and Chang, 2008). However, WEOM varied considerably among seasons, as well as among years, because WEOM is strongly affected by climatic conditions such as temperature and precipitation (Zsolnay, 2003). Therefore, comparisons among studies and ecosystems are extremely difficult. Despite this, the huge gap between temperate forests and Arctic soils suggested that Arctic WEOM pools are small compared to more temperate forest ecosystems. These findings can be confusing since Arctic soils stored relatively high amounts of SOM and highly labile C compared to such ecosystems. However, low WSOC and high WEOM C:N highlight the relative limitation of accessible nutrients for Arctic soil microbes and plants. Furthermore, these results may suggest tighter soil nutrient cycling in Arctic soils compared to temperate forests.

3.4.4 Assessing SOM Characteristics Using Multiple Approaches: Redundancy of Additional Information?

All performed analyses of SOM (density fractions, solid-state CPMAS ^{13}C NMR, and WEOM) may look similar and redundant because most SOM quality parameters are significantly correlated to each other (Table 3.4) and each method supports similar conclusions: organic surface soils contained relatively more fresh and labile SOM than mineral soils, and organic surface soils of Sub- and Low-Arctic ecosystems contained relatively more labile SOM than High-Arctic.

Density fractionation technique separates the fresh and partly-decomposed solid residues from SOM (Elliott and Cambardella, 1991; Gregorich et al., 2006; Six et al., 2002; Spycher et al., 1983; Swift, 1996; Zech et al., 1997). Alternatively, the solid-state CPMAS ^{13}C NMR technique provides a larger spectrum of the entire SOM qualities (Dria et al., 2002; Schnitzer, 1991; Simpson and Preston, 2008). Furthermore, the latter technique is only capable of estimating some 'lability' ratios of SOM (CC:MC, OAC:AroC, and OAC:AC). Finally, WEOM technique estimates the water-soluble SOM present in soil solution that is directly interacting with soil microbes and susceptible to be rapidly incorporated into soil C and N cycling processes (Chantigny, 2003; Zsolnay, 2003). Therefore, assessing SOM characteristics by using these three distinct approaches allowed me to highlight different pools of SOM. Similar conclusions supported by each of these methods simply enhance the strength of the conclusions.

Table 3.4: Correlation coefficients (Pearson) among soil organic matter quality parameters.

	SOC	Soil C:N	WSOC	WEOM C:N	C-LF	LF C:N	C-HF	HF C:N	CbyC	AC	AroC	OAC	CC
SOC	1	NS	0.72***	-0.21**	0.87***	-0.20**	0.66***	-0.25***	-0.45***	-0.27***	-0.55***	.068***	0.61***
Soil C:N		1	NS	0.49***	0.19**	0.70***	-0.40***	0.53***	-0.29***	NS	-0.24***	0.25***	0.31***
WSOC			1	NS	0.68***	-0.18**	0.53***	-0.20**	-0.46***	NS	-0.36***	0.41***	0.35***
WEOM C:N				1	NS	0.48***	-0.40***	0.27***	-0.14*	0.38***	NS	-0.27***	-0.23***
C-LF					1	NS	0.44***	-0.13*	-0.47***	-0.30***	-0.66***	0.76***	0.73***
LF C:N						1	-0.52***	0.71***	-0.16*	NS	NS	0.14*	0.22**
C-HF							1	-0.57***	-0.15*	NS	-0.20**	0.29***	0.18**
HF C:N								1	-0.16*	NS	NS	0.13*	0.20**
CbyC									1	-0.16*	0.54***	-0.63***	-0.56***
AC										1	NS	-0.47***	-0.46***
AroC											1	-0.80***	-0.84***
OAC												1	0.98***
CC													1

Significant at levels *: $P < 0.05$; **: $P < 0.01$; ***: $P < 0.001$; non-significant (NS) correlation. Soil organic carbon (SOC); Water-soluble organic carbon (WSOC); Water-extractable organic matter (WEOM); Light fraction (LF); Heavy fraction (HF); Carbonyl-C (CbyC); Alkyl-C (AC); Aromatic-C (AroC); O-Alkyl-C (OAC); Carbohydrates-C (CC).

3.4.5 Soil Organic Matter Characteristics in a Changing Climate

The effect of climate change on SOM decomposition has been widely studied in the Arctic (Christensen et al., 1999b; Illeris et al., 2004a; Oelbermann et al., 2008; Rinnan et al., 2008; Rodionow et al., 2006; Schmidt et al., 2002; Shaver et al., 1998; Welker et al., 2004). However, only few studies have attempted to elucidate differences among distinct Arctic ecosystems. A study showed no *in situ* temperature effect (+2 ^{o}C) on SOM decomposition in High-Arctic ecosystem (Ny-Ålesund, Svalbard) whereas *in situ* soil temperatures significantly increased SOM decomposition in Low-Arctic ecosystem (Abisko, Sweden) (Robinson et al., 1997). Therefore, the latter study suggested that SOM qualities, rather than soil temperature, might initially drive SOM decomposition in the Arctic. This conclusion was earlier supported by Nadelhoffer et al. (1991) who found that, under field moisture and temperature ranges, SOM qualities were a primary factors explaining differences of SOM decomposition rates among Arctic ecosystems and sites. Because the LF of SOM is composed primarily of fresh to partially decomposed plant residues (Elliott and Cambardella, 1991; Spycher et al., 1983), which are highly labile (Hassink, 1995a; Hassink, 1995b; Janzen, 1987) and can be rapidly modified by environmental changes such as climate change (Biederbeck et al., 1994; Janzen et al., 1992), soils storing a greater proportion of LF are at risk of losing SOM. For Churchill, Daring Lake, and Truelove organic soils, 53, 73, and 20% of the C was included in the LF, respectively, whereas 24, 19, and 14% of the C was included in the LF of mineral soils, respectively.

Most literature has demonstrated that the preferred materials for decomposition by soil microbes are in the OAC group, whereas AC, AroC, and CbyC groups tend to decompose more slowly. Soils from Churchill and Daring Lake had generally higher OAC:AroC and OAC:AC ratios than soils from Truelove, indicating that Sub-Arctic (Churchill) and Low-Arctic (Daring Lake) soils store relatively more labile SOM than High-Arctic soils (Truelove). Similar to Robinson et al. (1997), these results suggest that Sub-Arctic and Low-Arctic SOM is likely more sensitive to climate change than SOM from High-Arctic. Furthermore, the results suggest that organic surface soils from the Arctic are likely more sensitive to climate change than mineral surface soils.

In Arctic soils, the bioavailability of WEOM plays a large role in determining whether C is lost through leaching or gaseous emissions following its decomposition by heterotrophic soil microbes (Gundelwein et al., 2007; Neff and Hooper, 2002). However, it is extremely difficult to predict the real effects of climate change on soil WEOM because soil WEOM is temporally and spatially highly variable (Zsolnay, 2003). Nevertheless, with both higher temperatures and higher precipitations expected for most of the terrestrial Arctic (Huntington et al., 2005; Kattsov et al., 2005), it is likely that WEOM could play a greater role in soil nutrient cycling as well as soil C sequestration. The results from this study showed that WEOM was more vulnerable to climate change in organic than mineral surface soils because 1) low WSOC and WSON values were measured in mineral soils compared with organic soils and 2) different ecosystems (i.e., climates) did not differ in WSOC and WSON in mineral soils, whereas significant differences were measured for WSOC and WSON in organic soils.

3.5 Conclusions

This study greatly improved our knowledge related to SOM characteristics of three distinct Arctic soil ecosystems. All analyses of SOM (density fractions, solid-state CPMAS ^{13}C NMR, and WEOM) showed that organic surface soils (>17% C) contained relatively more labile C than mineral surface soils (<17% C). Furthermore, this study showed that Sub- and Low-Arctic ecosystems that produced high above-ground biomass stored a great amount of SOM as well as a high content of labile C compared to the High-Arctic ecosystem. Compared to temperate ecosystems, Arctic soils accumulated more labile C with a high release potential under more suitable conditions (i.e., warmer and wetter climates). Therefore, combining high SOM lability with high climate change severity could trigger a massive release of GHG into the atmosphere – enhancing the climate change effect. However, higher SOM decomposition could also lead to higher soil nutrient availability (e.g., higher soil N mineralization via SOM decomposition) for plants and therefore increase the C sequestration potential of Arctic ecosystems (i.e., more C absorbed by plants because nutrients are less limiting). Cryoturbation and soil moisture redistribution need to be considered as these processes directly and indirectly affect soil C storage as well as soil nutrient availability of Arctic soils. A better understanding of these mechanisms involved in soil C storage as well as soil nutrient cycling in the Arctic is needed.

Chapter 4 : Landscape-scale N Mineralization and Greenhouse Gas Emissions in Canadian Cryosols

Preface

Chapter 3 shows that Arctic soils store large amounts of highly labile SOM. However, knowledge of the ability of the soil to mineralize nitrogen and release greenhouse gases at the landscape scale is critical to predict and model future effects of climate change on Arctic SOM. This chapter represents a first investigation of some of the N and C cycling processes that are occurring in Arctic soils. Findings and gathered data from this study are used (Chapter 5) to determine the influence of SOM qualities on C and N cycling processes.

4.1 Abstract

Arctic soils store great amounts of soil organic matter (SOM) that are likely to be affected by future climate changes. Knowledge of the ability of the soil to mineralize nitrogen (N) and release greenhouse gases (GHG) at the landscape scale is critical to predict and model future effects of climate change on Arctic SOM. The objective of this study was to investigate how soil gross N mineralization and GHG emissions vary across landscapes and Arctic ecosystems. This study was conducted in three Arctic ecosystems: Sub-Arctic (Churchill, MB), Low-Arctic (Daring Lake, NWT), and High-Arctic (Truelove Lowlands, NU). The topography was divided into five landform units: 1) upper (Up), 2) back (Back), and 3) lower (Low) slopes for catena sites and 4) hummock (Hum) and 5) wedges (W) for hummocky sites (i.e., hummock in Churchill and ice-wedge polygons in Truelove). All sites were sampled near the end of their growing seasons (i.e., from two to three weeks before plant senescence). Soil gross N mineralization was measured *in situ* using a ^{15}N dilution technique, whereas soil GHG emissions (N_2O, CH_4, and CO_2) were measured *in situ* using a multicomponent Fourier transform infrared gas analyzer combined with an automated dark chamber. For all ecosystems, topography significantly influences soil gross N mineralization and CO_2 emissions. Topography had a slight impact on CH_4 emissions and no significant impact on N_2O fluxes most likely because net fluxes were extremely low throughout landscapes. Soil gross N mineralization and CO_2 emissions increase from Up, Back, to Low and from Hum to W landform units. For example, at Churchill, soil gross mineralization rates averaged 4 mg $N\text{-}NH_4^+$ kg^{-1} d^{-1} in upper slopes and progressively increased to about 25 mg $N\text{-}NH_4^+$ kg^{-1} d^{-1} in the lower slopes. Similarly, CO_2 emission rates at Daring Lake averaged 0.5 μmol CO_2 m^{-2} s^{-1} in upper slopes and progressively increased to about 2.3 μmol CO_2 m^{-2} s^{-1} in the lower slopes. Comparisons among ecosystems showed that Churchill (Sub-Arctic) had the highest gross N mineralization rates followed by Truelove (High-Arctic) and Daring Lake (Low-Arctic). Furthermore, Daring Lake had significantly higher CO_2 emissions than Churchill and no difference in CH_4 and N_2O emissions between both ecosystems were found. These findings suggest that all factors influencing C and N cycling processes such as climate and human induced changes may not have similar effects across landscapes or across Arctic ecosystems.

4.2 Introduction

The last decade has promoted a worldwide interest in Arctic ecosystems. This heightened interest in the Arctic can be explained by a limited knowledge of these ecosystems in the scientific community and the disproportion effects of global warming on this part of the planet. From 1990 to 2090, conservative climate models predict that the mean annual air temperatures will increase by 5 °C for most Canadian Arctic terrestrial areas, whereas an increase from 1 to 3 °C is expected for most of southern Canada (Huntington et al., 2005). Increasing air temperatures increase the potential for atmospheric circulation to transport moisture from lower to higher latitudes, resulting in warming accompanied by increases in precipitation, but decreases in the duration of snow cover (Huntington et al., 2005; Kattsov et al., 2005). By 2090, simulations indicate that precipitation in the Arctic will increase by approximately 12% with the greatest projected increase in autumn and winter when soils are mostly frozen (Kattsov et al., 2005). Therefore, these climate change projections for Arctic terrestrial ecosystems highlight the importance of considering soil moisture redistribution, which is mainly controlled by topography since continuous permafrost limits water infiltration into deep and frozen soil layers (Carey and Pomeroy, 2009; Yano et al., 2010).

Tundra landscapes are heterogeneous and can encompass a mosaic of wetland areas, riparian systems, well-drained heath lands, ridge-top vegetation and polar deserts (Sjögersten et al., 2006; Walker, 2000). At the landscape scale, topography plays an important role by affecting environmental conditions such as soil moisture, nutrients, and microclimate. At any point in a given landscape, the type and intensity of soil-forming processes are dominantly controlled by the redistribution of water, solutes, and sediments by hydrological and microclimatic processes (Pennock and Corre, 2001). The term landscape is used in a context to capture both landform and land use: landform combines the morphology of the surface and the parent material and land use includes the assemblage of plant communities that naturally occurs (Pennock and Veldkamp, 2006). Therefore, the scale at which the landscape research should be conducted is malleable. For example, hydrological studies of surface water (or surface water related studies such as N and C cycling studies) provide essential information over relatively short distances (<100 m;

from dry upper lands to wet lower lands) because the scale of the study must correspond to the scale of the processes studied (Pennock and Veldkamp, 2006).

Topographic position is an important factor controlling C storage in both Arctic and Boreal landscapes due to its influence on soil drainage (Hobbie et al., 2000). A recent study from Alaska demonstrated that topographic position played an important role in the Arctic by modifying water and soil nutrient redistributions, thus affecting soil N cycling dynamics throughout the landscape (Yano et al., 2010). In northern Sweden, soil hydrology was more important than soil temperature for explaining site differences and soil nutrient limitations (Weih, 1998). Furthermore, Welker et al. (2004) found that the differential C exchange responses of dry, mesic, and wet tundra to similar warming magnitudes appear to depend on the hydrologic redistribution (i.e., soil water regime affected by topography). It is likely that climate changes will have a differential effect across the Arctic landscape because: 1) topography creates different initial soil conditions (e.g., heavier soils with higher C content in lower positions compared with higher surrounding areas), 2) wind-protected areas created by topography enhances plant growth and soil microbial life (i.e., microclimates), and 3) importance of surface water redistribution will increase because precipitation will increase primarily in autumn and winter when soils are mostly frozen. Furthermore, landscape scale studies are essential for up scaling soil process information to regional, national, and global scales (Pennock and Veldkamp, 2006). Therefore, understanding the topographic effect across Arctic ecosystems is important for assessing climate change impacts on Arctic soil processes such as SOM accumulation, SOM decomposition, and soil greenhouse gas (GHG) emissions.

The effect of global warming on the SOM balance is unclear. It has been suggested that an increase of global temperature will increase soil nutrient loses as a result of increases in SOM decomposition and, hence, soil N mineralization and GHG emissions (Davidson and Janssens, 2006; Schmidt et al., 2002). However, an increase in soil N mineralization may also increase plant productivity (Jonasson et al., 1999), and hence increase soil C sequestration because plant materials generally have a higher C:N ratio than SOM (Weintraub and Schimel, 2005). A literature meta-analysis from Sub- to High-Arctic showed that increasing *in situ* soil temperatures using different warming techniques (e.g., electrical heat-resistance ground cables,

greenhouses, vented and unvented field chambers, overhead infrared lamps, and passive night time warming) significantly increased soil CO_2 emissions, N mineralization, and above-ground plant biomass (Rustad et al., 2001). In the Arctic, most of the plant community composition shifts expected to occur with climate change will likely result in a greater dominance of deciduous shrubs and trees (Kummerow et al., 1987; Sturm et al., 2001a). Compared to any other plant in the Arctic, deciduous shrubs and trees store a large quantity of C in their above-ground biomass (Hobbie, 1996) and protect soil from extreme temperatures by increasing winter snow depth (Sturm et al., 2001b). However, Havström et al. (1993) have shown that different treatments such as warming, moisture increase, and nutrient addition produced very different plant responses in different latitudes and ecosystems. A study from the Low-Arctic recently showed that tall shrubs were growing exclusively where high soil N mineralization was occurring even though soil microbial and fungal communities were similar to a site with low productivity (Buckeridge et al., 2010b). Therefore, because Arctic soils are complex and heterogeneous, plant community composition shifts will not happen throughout Arctic landscapes with the same intensity, but will depend on many factors related to soil moisture and fertility. These results suggest that the response of plant community to climate change will strongly depend on the ability of the soil to provide N via SOM decomposition. Therefore, measuring the ability of the soil to provide N (i.e., soil N mineralization) as well as release GHG (i.e., soil GHG emissions) at the landscape scale will give some insight into the fate of Arctic SOM; whether Arctic soils will continue to accumulate SOM (i.e., net sink), or instead become an important source of greenhouse gases (GHG) via SOM decomposition (i.e., net source). **The objective of this study was to investigate how soil gross N mineralization and GHG emissions vary across landscapes and Arctic ecosystems.**

4.3 Materials and Methods

4.3.1 Study Locations

This study was conducted in three distinct Arctic ecosystems: High-Arctic (Truelove, NU), Low-Arctic (Daring Lake, NWT), and Sub-Arctic (Churchill, MB) (Figure 3.1). Truelove and Daring

Lake were sampled in 2008 and Churchill was sampled in 2009. All sites were sampled at the end of their growing seasons, from two to three weeks before plant senescence.

4.3.1.1 Sub-Arctic: Churchill

The Sub-Arctic ecosystem is located in Churchill, Manitoba, Canada (58° 45'N; 93° 51'W). Between 1996 and 2006, a mean annual temperature of -5.8 ± 1.6 °C and a mean annual precipitation of 501.2 ± 89.1 mm were recorded (Environment Canada, 2011). The region is underlain by continuous permafrost of about 80 m thickness (Dredge, 1992). Further details are provided in Chapter 4, Section 4.3.1.1.

The upper slope of the beach crests had relatively low vegetation cover as well as high gravel and rock content in the soil. Lichen species, as well as *Dryas integrifolia*, were the more dominant vegetation types. The back slope of the raised beaches had taller vegetation. Some trees such as *Picea glauca* and small shrubs such as *Vaccinium uliginosum* were particularly abundant. The lower slope had high vegetation diversity growing on a silty and wet soil material. *Carex aquatilis* were found in wet parts whereas *Vaccinium uliginosum* was found in driest locations. The peaty and mossy soils associated with hummocks had two distinct vegetation types: lichens and evergreen plants were abundant on hummocks, whereas the wind-protected soils between hummocks favoured dwarf birch and *Carex* vegetation types. *Empetrum nigrum* was abundant on hummocks and *Vaccinium uliginosum* was abundant between hummocks (i.e., wedge). A well-detailed vegetation book of the Churchill lowland areas has been published by Johnson (1987).

4.3.1.2 Low-Arctic: Daring Lake

The Low-Arctic ecosystem is located in Daring Lake, Northwest Territories, Canada (64^{o}E 50'N; 111^{o}E 38'W) approximately 300 km northeast of Yellowknife, and 70 km north of the tree line. Seven-year climate records from a permanent weather station indicated a mean annual air temperature of -9.0 ^{o}C (Nobrega and Grogan 2008). The entire region is underlain by a thick permafrost layer (>160m) with the summer active-layer depths ranging from 15 to 120 cm depending on local parameters such as vegetation cover, soil materials, and soil moisture (Dredge et al., 1999). Further details are provided in Chapter 4, Section 4.3.1.2.

The upper slope soils of the esker had low vegetation cover as well as high gravel and rock contents. Lichens and *Empetrum nigrum* were the predominant species. The back slopes of the esker had high vegetation diversity, including several taller shrub species, growing on sandy material. Some vascular species such as *A. alpina* and *B. glandulosa* were particularly abundant. The lower slopes of the esker had high vegetation diversity growing on silty and/or organic materials (i.e., poorly sorted sediments) sometimes associated with mud boils. *Carex* spp. and *Eriophorium vaginatum* were particularly abundant. These landform units have been studied at Daring Lake by Nobrega and Grogan (2008), and collectively represent approximately 63% of the Low-Arctic landscape cover (Walker et al., 2005).

4.3.1.3 High-Arctic: Truelove

The High-Arctic ecosystem is located in Truelove, Nunavut, Canada (75^{o}E 33'N; 84^{o}E 40'W) Truelove is a polar oasis (~43 km^2) situated on the northern coast of Devon Island (~54,000 km^2). The climate data available for Truelove is very limited. Between 1996 and 2006 at Grise Fiord (~80 km north Truelove), a permanent weather station measured a mean annual temperature of -14.2 ± 1.0 °C and a mean annual precipitation of 183.8 ± 34.2 mm (Environment Canada, 2011). The entire coastal lowland region was underlain by a thick permafrost layer (>200m) (Brown, 1977). Further details are provided in Chapter 4, Section 4.3.1.3.

The upper slopes of the beach crests were well-drained zones with high gravel and cobble contents. Lichens were the predominant vegetation. It has been estimated that the lichen vegetation community associated with upper slopes accounts for approximately 6% of the terrestrial area of Truelove. The back slopes of the raised beaches were a moderately drained transition zone between the upper and lower slopes characterized by a pronounced hummocky surface (e.g., 15 cm x 15 cm). *Dryas integrifolia* and *Cassiope tetragona* were the dominant species. It has been estimated that the vegetation community associated with the back slope landform unit accounts for approximately 8% of the terrestrial area of Truelove (Muc and Bliss, 1977). The lower slope landscape units were poorly drained zones that retained most of the water that drained from the surrounding area. Reducing conditions were also observed for some points. The lower slope vegetation (e.g., graminoids and bryophytes) was the most common community of the lowland and covers approximately 26% of the terrestrial lowland system. On boggy

wetlands and where winter temperatures are harsh and snow cover is thin, hummocks (i.e., peat polygons) have developed. The peaty and mossy soils associated with hummocks had two distinct vegetation types: lichens were abundant on hummocks, whereas the wind-protected and moist soils between hummocks favoured mosses and graminoids. A more detailed vegetation description of this area has been published by Bliss (1977).

4.3.2 Method of Sampling

At each site, the sampling locations were evenly distributed among upper (Up), back, and lower (Low) landform units for catena sites and among wedge (W) and hummock (Hum) for hummock sites (Figure 4.1 and Table 4.1). Because there is little prior knowledge of within-landform variability, the grid sampling method was chosen for each landform, except for hummock sites, where one sample for each repeated landform was taken. For each landform, sampling points were evenly spaced by either 5 m (Churchill and Daring Lake) or 6 m (Truelove) except for hummock sites, where spacing between points depended on the hummock locations and organizations. The sampling area for each sampling point covered 0.3 m^2 (i.e., 20 cm dia.). Field measurements and sampling took place over a three-day period. On day one, soil GHG emissions were measured (see Section 4.3.5); soil temperature (T) also was measured within each sampling area (i.e., during GHG measurements) using an ECH2O probe (ECH2O-TE/EC-TM, Decagon Devices). On day two, three 0-10 cm intact soil sub-samples per sampling point were gently cut with a soil knife (i.e., to keep the soil micro-sites as intact as possible) and placed into plastic cores (Histoplex Histology Containers, 500 mL). When stone content exceeded approximately 10% of the volume (estimated visually), the soil was gently sieved to <4.75 mm. Two incubation cores were used to estimate gross N mineralization (over days two and three) and the third was frozen and shipped to Saskatchewan for further laboratory analyses. In the laboratory, soils were thawed, the roots were removed, the soils were sieved to <2 mm, and air-dried prior to analysis.

4.3.3 Soil General Analysis

Soil gravimetric water content (moisture) was calculated using oven weight loss (105°C for 24 h). Soil pH was measured in 0.01 *M* $CaCl_2$ (Hendershot et al., 2008) using a portable pH meter (model SP80 PC pH/cond, VWR International, Mississauga, ON).

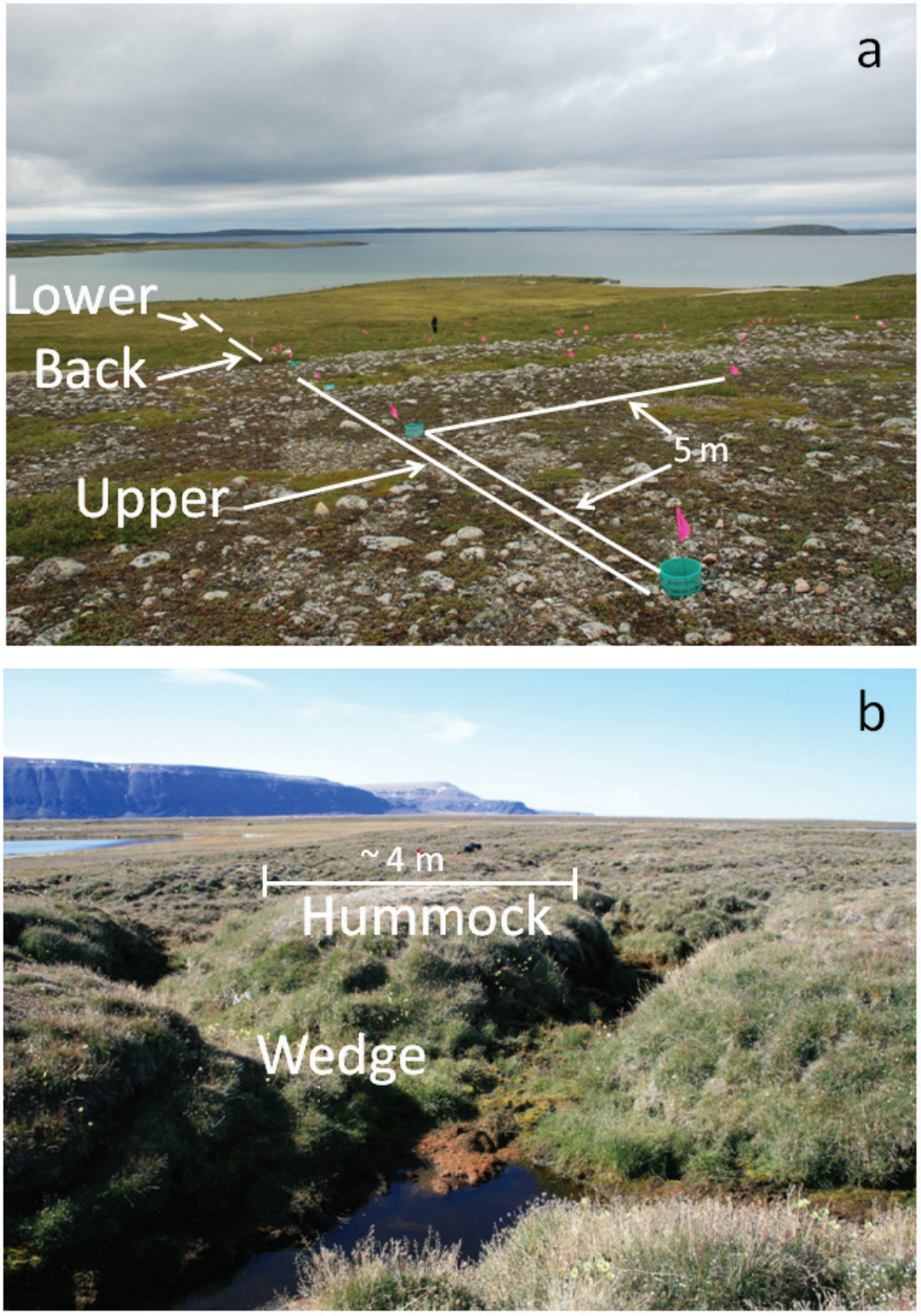


Figure 4.1: Two types of topography sampled for this study and their associated landform units: a) Catena and b) Hummocks (Churchill) or Ice-wedge polygon (Truelove).

Table 4.1: Ecosystems, sites, and landforms sampled for this study.

Ecosystem *Site* Landform†	Location	Dominant Soil	Dominant Vegetation
Sub-Arctic	**Churchill**		
Dump	58°43'51''N; 93°47'18''W		
Up (n=12)		Brunisolic Eutric Static Cryosol	Lichens
Back (n=12)		Histic Regosolic Static Cryosol	Shrubs
Low (n=12)		Gleysolic Turbic Cryosol	Bryophyte & Shrubs
Buggy	58°45'5''N; 93°51'24''W		
Up (n=12)		Regosolic Static Cryosol	Lichens & Flowering plants
Back (n=12)		Cumulic Regosolic Static Cryosol	Lichens & Shrubs
Low (n=12)		Cumulic Gleysolic Static Cryosol	Bryophytes & Graminoids
Bear	58°45'20''N; 93°56'58''W		
Up (n=12)		Regosolic Static Cryosol	Lichens & Flowering plants
Back (n=12)		Histic Eutric Static Cryosol	Shrubs
Low (n=12)		Gleysolic Static Cryosol	Bryophytes & Graminoids
Hummock	58°43'48''N; 93°47'25''W		
Hum (n=15)		Histic Regosolic Turbic Cryosol	Lichens
W (n=15)		Regosolic Turbic Cryosol	Shrubs
Low-Arctic	**Daring Lake**		
Saguenay	64°52'27''N; 111°34'41''W		
Up (n=20)		Orthic Dystric Static Cryosol	Lichens
Back (n=20)		Eluviated Brunisolic Dystric Static Cryosol	Shrubs & Lichens
Low (n=20)		Histic Regosolic Turbic Cryosol	Bryophytes & Graminoids
High-Arctic ‡	**Truelove**		
Gaspésie	75° 39' 59''N; 84° 37' 55''W		
Up (n=10)		Brunisolic Eutric Static Cryosol	Lichens
Back (n=10)		Brunisolic Eutric Turbic Cryosol	Mosses & Lichens
Low (n=10)		Gleysolic Turbic Cryosol	Bryophytes & Graminoids
Polygon	75° 40' 12''N; 84° 36' 43''W		
Hum (n=12)		Fibric Organic Turbic Cryosol	Lichens
W (n=12)		Fibric Organic Turbic Cryosol	Bryophytes & Graminoids

† Landform units: Up=Upper slope; Back=Back slope; Low=Lower slope; W=Wedge of polygon (Truelove) or hummock (Churchill); Hum=Center of polygon (Truelove) or hummock (Churchill). ‡ At Truelove, Gaspésie site refers to a raised beach sequence and polygon site refers to the ice-wedge polygon site as described by Bliss (1977).

Soil organic carbon (SOC) and total nitrogen (TN) were determined by combustion using a C analyzer (model C632, Leco Corporation, St. Joseph, MI) and a CNS analyzer (model Leco-2000, Leco Corporation, St. Joseph, MI), respectively. To remove inorganic C, all samples were acid-treated with 6% H_2SO_3 prior to SOC analysis (Skjemstad and Baldock, 2008).

4.3.4 Soil N Mineralization

Soil gross N mineralization was measured using the N isotope dilution technique (Davidson et al., 1991; Hart et al., 1994a). Two intact cores per sampling location were each injected 13 times with 1.7 mL of $(^{15}NH_4)_2SO_4$ solution (15 µg N mL^{-1} at 99% ^{15}N). The injections were uniformly distributed throughout the entire soil volume. After injection, the first core (time 0) was incubated for 15 minutes and then extracted with 2 *M* KCl. The second core (time 24) was incubated *in situ* for 24 h and then extracted with 2 *M* KCl. The incubation core lids were used to prevent water addition from rain or dew but were not tightly sealed in order to maintain aerobic conditions. All 2 *M* KCl extracts were filtered through 11µm filter paper (No. 1, Whatman Inc., Piscataway, NJ) following the Maynard et al. (2008) procedure. Filtered extracts were stored frozen until analysis.

Ammonium concentrations from the filtered extracts were determined colorimetrically following the phenolhypochlorite method (Solorzano, 1969) using a SmartChem 200 discrete autoanalyzer (Westco Scientific, Brookfield, CT).

A 10-mL sub-sample of the filtered extract was used to determine $^{15}N\text{-}NH_4^+$ content (Stark and Hart, 1996). Approximately 0.3 g of magnesium oxide (MgO) was used to convert $N\text{-}NH_4^+$ into $N\text{-}NH_3$. Ammonia was then trapped on a paper disk acidified with 10 µL of 2.5 *M* $KHSO_4$. The disk was sealed between two Teflon strips (Rona X-Pert, Rona Inc., Boucherville, QC). The 10-mL sub-sample, MgO, and sealed paper disk were gently shaken (130 rpm for 7 days) in an airtight 60-mL Nalgene bottle (High-Density polyethylene, VWR International, Mississauga, ON). Thereafter, the sealed paper disk was dried (50 °C for 1 hour), removed from its Teflon casing, and inserted into a tin capsule (D1008, Elemental Microanalysis Ltd, Okehampton Devon, UK) for isotopic determination. The $^{15}N\text{-}NH_4^+$ concentration was determined using a dual-inlet, double-collector isotope ratio mass spectrometer (VG Micromass 602E, Isotech,

Middlewich, UK). Gross N mineralization (mg N kg^{-1} soil d^{-1}) rates were calculated according to equation 5.1 (Hart et al., 1994a)

$$\text{Gross N mineralization} = \frac{[NH_4^+]_0 - [NH_4^+]_t}{t} * \frac{\log \frac{APE_0}{APE_t}}{\log \frac{[NH_4^+]_0}{[NH_4^+]_t}} \quad (4.1)$$

where t is the time (days), and APE is the atom % ^{15}N excess.

4.3.5 Soil GHG Emissions

The GHG emissions at Churchill and Daring Lake were determined *in situ* using a Multicomponent Fourier Transform Infrared Gas Analyzer (Gasmet DX-4015, Gasmet Technology, La Prairie, QC) coupled with an automated dark chamber (model 8100-104, Li-Cor Biosciences, Lincoln, NE) (Lamb et al., 2011). Gas concentrations were calculated from the infrared spectra using the Calcmet^{TM} software (version 2005.1). A 0.032-m^2 polyvinyl chloride cylinder (PVC) was used to ensure contact between the soil surface and the chamber. During measurement, the chamber was closed 5 min and the gas concentration integrated over a 30-s interval at Daring Lake and a 20-s interval at Churchill. Between measurements, the chamber was kept open, connected to the gas analyzer, and flushed with ambient air for more than 3 min (i.e., until gas reading stability was reached). Preliminary tests showed that a clear accumulation of GHG in the system started 2 min after the chamber close, whereas gas concentrations mostly increased in near-linear fashion thereafter. Therefore, the first derivative of gas concentration (ppm) and time (s) was taken to estimate the gas fluxes (Davidson et al., 2002). The detection limits of the gas analyzer are: N_2O (15 ppb), CH_4 (0.1 ppm), and CO_2 (50 ppm) (Farrell, personal communication), whereas the measured GHG concentrations ranges were: N_2O (0.31-0.50 ppm), CH_4 (0.6-2.9 ppm), and CO_2 (312-458 ppm).

The GHG emissions were measured following several time-blocks that included an even number of each landform units. At Churchill, each time-block was composed of 3 Ups, 3 Backs, and 3 Lows landform units (Appendix D). At Daring Lake, each time-block was composed of 4 Ups, 4 Backs, and 4 Lows landform units. For both Churchill and Daring Lake, each time-block took

approximately 1.5 hours to be measured. At the Churchill hummock site, W and Hum landform units were measured alternately throughout the sampling day.

4.3.5 Statistical Analysis

Variance homogeneity was evaluated with the Levene test. Data were either log or exponentially transformed when not normally distributed. Two-way ANOVAs (type III of squares) were used to determine differences between ecosystems and landform using general linear model procedure in SPSS version 13 for Windows (SPSS Inc., 2004). Two-way ANOVAs were also used in similar contexts (Park and Burt, 2002; Tomer et al., 2006). An equally-spaced sampling protocol (5 or 6 m) was used to minimize any experimenter bias. A recent study estimated a soil moisture spatial dependency with less than 1.7 m ranges for three Arctic ecosystems (Banerjee et al., 2011), making spatial dependency among sampling locations unlikely.

4.4 Results and Discussion

4.4.1 Soil Gross N Mineralization and Topography

All landform units from all ecosystems were relatively active and mineralized considerable amounts of N (Figure 4.2). For both catena and hummock sites, gross N mineralization rates were significantly different among landforms and significant interactions suggested that this was consistent throughout the Arctic (Table 4.2). Soil gross N mineralization tended to increase progressively from Up, Back, to Low and from Hum to W landform units (Figure 4.2). In the Arctic, above ground biomass is a strong indicator of local soil N availability (Potter et al., 1995; Robinson et al., 1998). For example, at Daring Lake, tall shrubs grow on soils that have high gross N mineralization rates and high net mineralized N, compared to similar soils without shrubs that have lower gross N mineralization rates (Buckeridge et al., 2010b; Chu and Grogan, 2010).

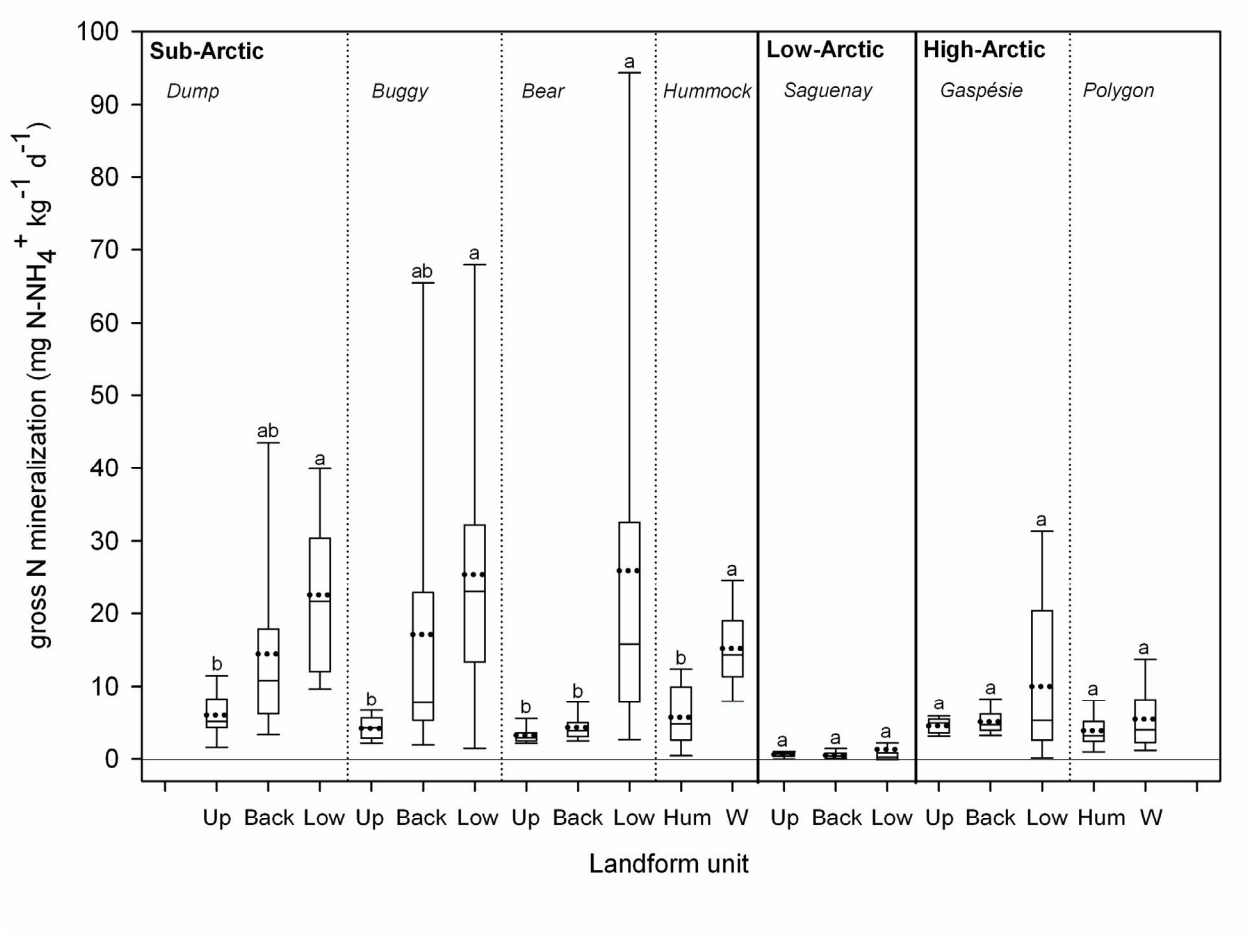


Figure 4.2: Soil gross N mineralization rates between ecosystem and site sampled for this study. The lower boundary of the box indicates the 25th percentile, the line within the box indicates the median, the dashed line in the box represents the mean, the dashed line in the box represents the mean, the upper boundary of the box indicates the 75th percentile, and the whiskers above and below the box indicate the 90th and 10th percentiles. For each site, differences between landform units were determined using one-way ANOVA and Games-Howell at a level α=.05 was used as post-hoc test (equal variances not assumed). Upper slope (Up); Back slope (Back); Lower slope (Low); Hummock (Hum); Wedge (W).

Table 4.2: Statistical comparisons of soil N and C cycling processes and soil properties among ecosystems (E) and between landforms (L). †

	Catena Sites			Hummock Sites		
	E	L	E x L	E	L	E x L
	P	*P*	*P*	*P*	*P*	*P*
d.f.	2	2	4	1	1	1
Soil N and C Cycling						
Gross N mineralization ¶	<0.001	0.004	<0.001	<0.001	<0.001	0.027
N_2O emissions	0.584	0.755	0.682		0.469	
CH_4 emissions	0.601	0.044	0.047		0.095	
CO_2 emissions §	<0.001	<0.001	0.003		<0.001	
Soil Properties						
Temperature	<0.001	<0.001	<0.001	<0.001	<0.001	0.084
Moisture §	0.010	<0.001	<0.001	<0.001	0.030	0.012
pH	<0.001	<0.001	0.003	<0.001	<0.001	<0.001
SOC ¶	<0.001	<0.001	<0.001	<0.001	0.114	<0.001
Soil C:N §	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

† Multiple-factors ANOVAs (type III of squares) among ecosystems and landform. Ecosystem: Sub-Arctic (Churchill), Low-Arctic (Daring Lake), and High-Arctic (Truelove). Landforms: Upper slope, back slope, lower slope for catena sites; hummock and wedge for hummock sites. For hummock sites, GHG data were available only for Churchill. Logarithm (§) or exponential (¶) transformations applied to meet normality. SOC: Soil organic matter.

A progressive increase in N availability from dry heath, moist heath, to meadow Arctic ecosystems was reported by Weih (1998) and by Chu and Grogan (2010). Furthermore, Biasi et al. (2005) also found higher gross N mineralization rates on W compared to Hum in two distinct Siberian ecosystems. In order to explain this phenomenon, several hypotheses related to soil microbial activities and plant growth are proposed. First, redistribution of water-soluble soil nutrients from up-slope to down-slope with water, wind, and snow (Fahnestock et al., 2000; Kummerow et al., 1987) creates more fertile conditions for soil microbial biomass and plant growth in lower-slope positions (Christensen et al., 1999a; Schimel et al., 1985; Schimel et al., 2004). In addition, Up landform areas are exposed to strong winds resulting in thin snow accumulation, high temperature variations, and dry soil conditions, which all lead to reduced soil microbial activity and plant growth (Fahnestock et al., 2000; Giblin et al., 1991). The tallest vegetation is found on lower slope areas, which locally slows down the wind, and increases snow accumulation (Sturm et al., 2001b), decreases temperature variations, and increases local soil water content, which all lead to high soil microbial activity and greater plant growth. Finally, high soil microbial activity and plant growth increase SOC, and consequently soil water holding capacities and soil nutrient sorption capacities, which further augment soil microbial activity, N mineralization, and plant growth (Barrett and Burke, 2000; Burke, 1989; Giblin et al., 1991; Robinson et al., 1995). Small landscape variations result in big differences in microbial activity, fertility, and plant productivity in resource-limited ecosystem with a harsh climate.

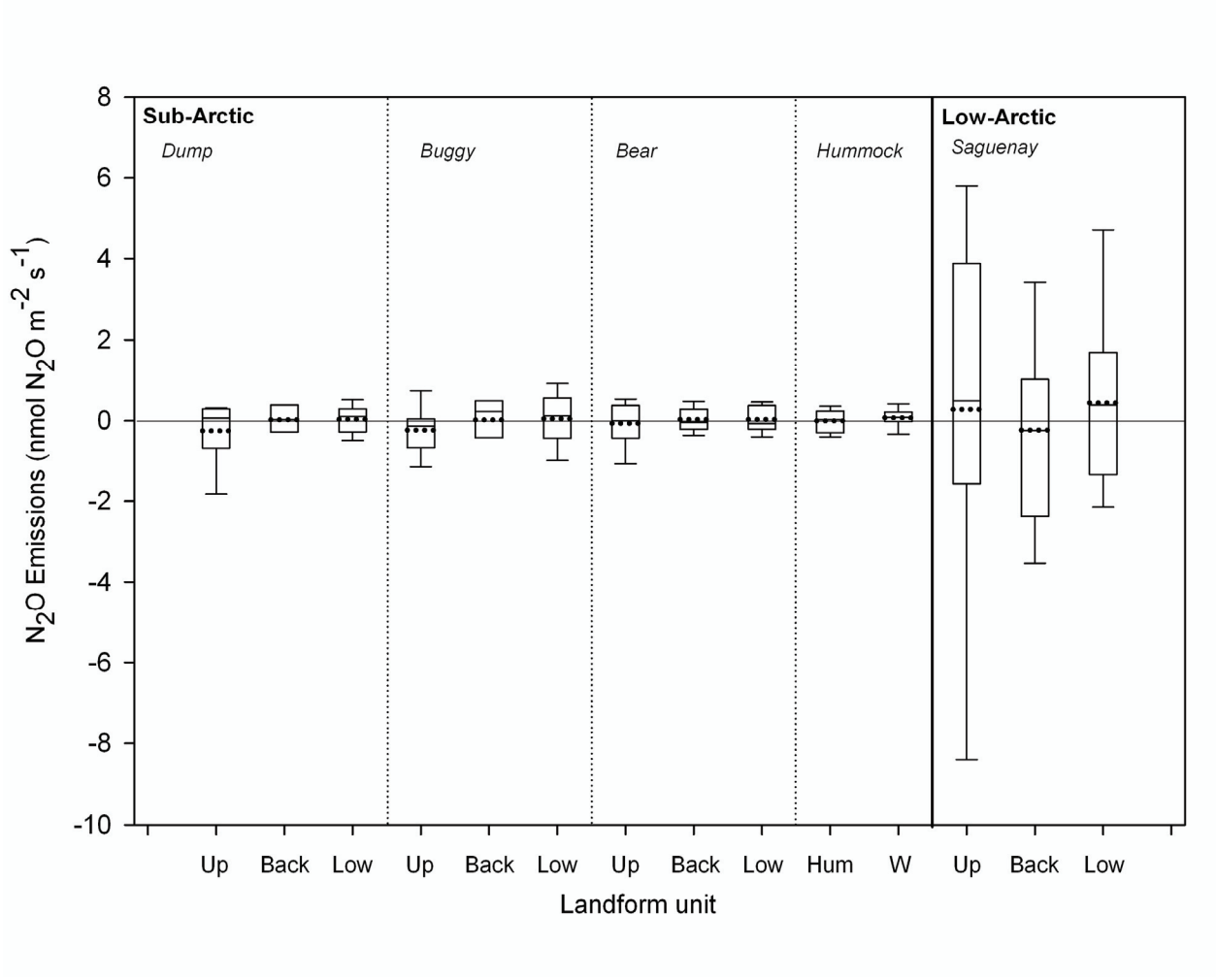


Figure 4.3: Soil N_2O emission rates between ecosystem and site sampled for this study. The lower boundary of the box indicates the 25th percentile, the line within the box indicates the median, the dashed line in the box represents the mean, the dashed line in the box represents the mean, the upper boundary of the box indicates the 75th percentile, and the whiskers above and below the box indicate the 90th and 10th percentiles. Upper slope (Up); Back slope (Back); Lower slope (Low); Hummock (Hum); Wedge (W).

4.4.2 Soil GHG Emissions and Topography

4.4.2.1 N_2O Emissions

Very low net emissions of N_2O were measured on all landform units (Figure 4.3). Several studies from different Arctic ecosystems also have shown very low N_2O emissions (Christensen et al., 1999a; Churchill, 2007; Rodionow et al., 2006; Sorensen et al., 2006), indicating that Sub- and Low-Arctic soils are N conservative soils and can also act as N_2O sinks (Buckeridge et al., 2010a). For both ecosystems, the results showed no significant trend between landform unit and N_2O emissions (Table 4.2), most likely because very low N_2O fluxes were measured [Churchill (mean): -0.03 nmol N_2O m^{-2} s^{-1}; Daring Lake (mean): 0.16 nmol N_2O m^{-2} s^{-1}]. Therefore, unlike other ecosystems (Pennock et al., 1992; Van Kessel et al., 1993), topography is not a major factor affecting N_2O emissions. Because Arctic ecosystems are N conservative, N_2O emissions from Arctic soils are perhaps not as sensitive to landscape (e.g., water content) as might be the case in other more temperate ecosystems that produce more N_2O (Siciliano et al., 2009). Nevertheless, a recent study from the High-Arctic showed that the greatest potential for N_2O production occurred in the wettest area of the landscape (Ma et al., 2007). In addition, Ma et al. (2007) showed that ammonium stimulated N_2O emissions to a greater extent than nitrate, suggesting that nitrifier denitrification was a process occurring in these soils. Nitrifier denitrification is a pathway of nitrification which converts ammonium to N_2O by several oxidation and reduction pathways. Low oxygen contents and high N concentrations are two major conditions that promote the nitrifier denitrification pathway (Wrage et al., 2001). These latter findings were consistent with Christensen et al. (1999a) who found that landform units associated with high NH_4^+ productions (i.e., N gross mineralization) also were associated with high N_2O emissions. Weak but significant positive correlations between N_2O emissions and soil gross N mineralization were observed for both ecosystems (Churchill: r=0.218, P=0.021; Daring Lake: r=0.333, P=0.016), suggesting that nitrifier denitrification is an active N pathway under field soil conditions. Therefore, topography may potentially affect both N_2O production pathways (nitrifier denitrification and denitrification) since denitrification is mainly controlled by soil moisture and nitrifier denitrification is mainly affected by NH_4^+ production which, as shown (Table 4.2) is strongly affected by the topography.

4.4.2.2 CH_4 Emissions

Very small trends between topography and CH_4 emissions were measured (Table 4.2), most likely because low net emissions of CH_4 were measured on all landform units (Figure 4.4). On average, Churchill emitted 0.09 nmol CH_4 m^{-2} s^{-1} and Daring Lake emitted 0.47 nmol CH_4 m^{-2} s^{-1}. Several studies from different Arctic ecosystems also measured low CH_4 emissions (Christensen et al., 1999a; Christensen et al., 2000; Churchill, 2007; Rodionow et al., 2006; Rouse et al., 1995). At Churchill, Rouse et al. (1995) showed that the marsh, ponds and wet fen emitted significant net CH_4 emissions whereas moist fen and bog produced very small CH_4 emissions. Although large, Churchill moisture values (Table 4.3) were within the typical ranges for this area (Churchill, 2007). As others found before, this study shows that topography plays a slight but significant role in CH_4 emissions in the Arctic. However, because this study sampled a very large spectrum of soil moisture (Table 4.3), the results may suggest that CH_4 emissions from Arctic mineral-dominated soils, such as those sampled for this study, are not highly sensitive to change in soil moisture. Similarly, four years of weekly measurements found that in the Arctic net CH_4 fluxes and subsurface soil properties (e.g., moisture, temperature, thaw depth, etc.) are largely unrelated (Whalen and Reeburg, 1992).

These findings are unusual because most of the studies that measured CH_4 emissions from Arctic soils exclusively focused on peatlands (i.e., organic-dominated soils). Other important factors may explain our CH_4 emission variations in such soil ecosystems. As suggested before (Christensen et al., 1999a; Rouse et al., 1995; Wagner et al., 2005), studying other soil attributes, such as microbial communities responsible for CH_4 consumption and production, may well give more insightful results for better understanding of CH_4 emissions from Arctic soils at the landscape scale.

4.4.2.3 CO_2 Emissions

Results showed that soils from all landform units and all ecosystems were active and release CO_2 to the atmosphere (Figure 4.5). For both catena and hummock sites, CO_2 emission rates were significantly different among landforms and significant interaction suggested that this was consistent throughout Arctic (Table 4.2).

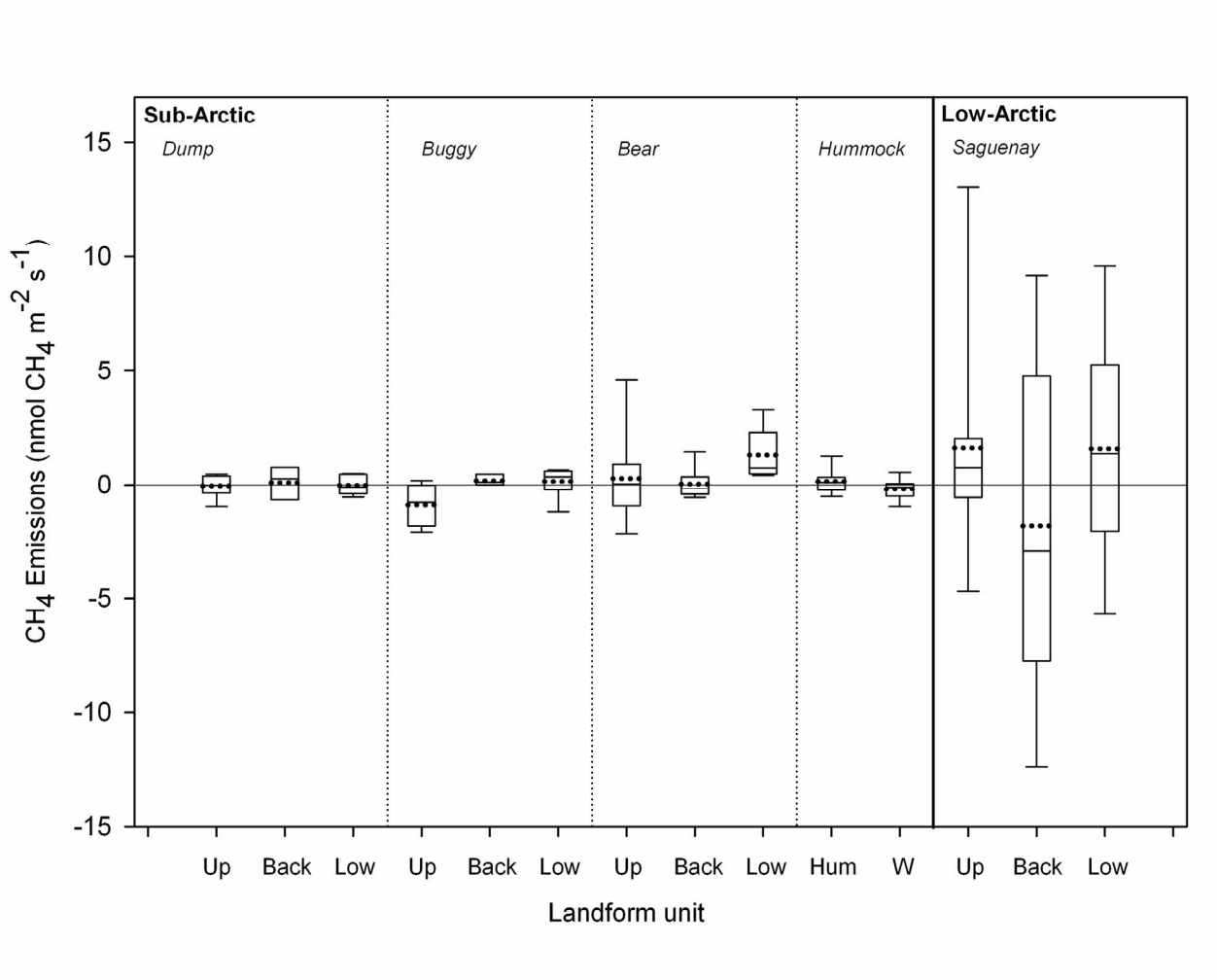


Figure 4.4: Soil CH_4 emission rates between ecosystem and site sampled for this study. The lower boundary of the box indicates the 25th percentile, the line within the box indicates the median, the dashed line in the box represents the mean, the dashed line in the box represents the mean, the upper boundary of the box indicates the 75th percentile, and the whiskers above and below the box indicate the 90th and 10th percentiles. Upper slope (Up); Back slope (Back); Lower slope (Low); Hummock (Hum); Wedge (W).

Table 4.3: General soil (0-10 cm) properties between ecosystems, sites, and landform units.

Ecosystem (Location) *Site* Landform †	n	Temperature	Gravimetric Moisture	pH	SOC	Soil C:N
		---- °C ----	--- g g^{-1} ---		-- g $100g^{-1}$ --	
Sub-Arctic (Churchill)						
Dump						
Up	12	9.0(1.4)	0.2(0.0)	6.8(0.1)	6.9(2.2)	16.8 (3.1)
Back	12	5.2(0.6)	1.4(0.7)	6.3(0.2)	32.4(11.8)	21.6(4.7)
Low	12	3.8 (0.6)	2.5(0.6)	5.4(0.3)	45.2(0.9)	19.5(4.7)
Buggy						
Up	12	12.0(2.5)	0.1(0.1)	6.8(0.1)	4.1(2.4)	11.4(3.0)
Back	12	5.6(1.2)	1.8(0.9)	6.4(0.3)	22.4 (12.0)	21.4(3.5)
Low	12	7.7(2.4)	5.5(1.2)	7.0(0.1)	37.8(4.0)	18.1(4.1)
Bear						
Up	12	10.3(0.8)	0.1(0.0)	6.5(0.1)	4.8(1.4)	26.3(2.2)
Back	12	8.8(1.2)	0.3(0.2)	6.4(0.1)	6.3(1.5)	25.0(3.5)
Low	12	5.8(0.7)	2.1(0.5)	6.4(0.2)	18.2(7.3)	24.0(11.4)
Hummock						
Hum	15	7.7(0.8)	2.2(0.3)	4.1(0.5)	47.1(1.7)	33.3(14.9)
W	15	5.9(0.8)	2.2(0.7)	6.0(0.3)	39.4(6.9)	15.0(3.0)
Mean		7.4(2.6)	1.7(1.6)	6.1(0.8)	24.9(17.4)	21.2(8.9)
Low-Arctic (Daring Lake)						
Saguenay						
Up	20	13.6(1.9)	0.5(0.2)	4.3(0.3)	4.4(2.9)	19.5(2.8)
Back	20	13.1(1.5)	0.6(0.3)	3.8(0.3)	7.2(7.9)	27.9(4.9)
Low	20	13.4(1.1)	2.3(1.5)	3.6(0.4)	25.8(19.0)	32.5(7.6)
Mean		13.3(1.5)	1.1(1.2)	3.9(0.4)	12.5(15.2)	26.6(7.6)
High-Arctic (Truelove)						
Gaspésie						
Up	10	15.4(2.1)	0.6(0.3)	6.3(0.1)	23.6(7.5)	14.9(1.9)
Back	10	12.1(1.5)	1.3(0.3)	6.5(0.0)	25.4(3.5)	13.7(0.9)
Low	10	9.4(1.5)	2.2(1.9)	6.5(0.1)	21.2(11.8)	15.2(2.6)
Polygon						
Hum	12	12.5(1.6)	1.0(0.3)	6.0(0.2)	29.8(1.3)	14.3(0.5)
W	12	11.9(1.6)	1.5(0.5)	5.7(0.2)	33.2(6.4)	16.9(3.3)
Mean		12.3(2.5)	1.3(1.0)	6.2(0.4)	27.0(8.0)	15.0(2.3)

Mean (std dev). † Landform units: Up=Upper slope; Back=Back slope; Low=Lower slope; W=Wedge of polygon (Truelove) or hummock (Churchill); Hum=center of polygon (Truelove) or hummock (Churchill).

As with gross N mineralization, CO_2 emissions tended to increase from Up, Back, to Low and from Hum to W landform units to a greater extent than other measured GHG (i.e., N_2O and CH_4) (Figure 4.5). For example, Churchill upper soils emitted on average 0.3 μmol CO_2 m^{-2} s^{-1}, whereas lower soils emitted 0.6 μmol CO_2 m^{-2} s^{-1}. At Daring Lake, Up slope emitted in average 0.5 μmol CO_2 m^{-2} s^{-1}, whereas Low slope emitted 2.3 μmol CO_2 m^{-2} s^{-1}. A progressive increase of CO_2 emissions following soil moisture gradients in the Arctic has been reported in the literature (Nobrega and Grogan, 2008; Sjögersten et al., 2006). The same factors influencing soil gross N mineralization (e.g., high soil moisture and SOC leading to high soil microbial activities) may explain these trends, suggesting that soil CO_2 emissions and soil gross N mineralization are tightly related. However, poor correlations between CO_2 emissions and gross N mineralization (Churchill: r=0.301, *P*=0.001; Daring Lake: r=-0.007, *P*=0.959) suggest that CO_2 emissions and soil N mineralization were not directly linked. Nevertheless, soil CO_2 emissions and soil gross N mineralization followed similar trends throughout the landscapes.

Unlike CH_4 and N_2O, CO_2 is not produced exclusively by microorganisms; other organisms such as plants and small soil animals can also release CO_2. The dark chamber method for assessing CO_2 fluxes has the advantage of measuring the whole ecosystem CO_2 emissions but the inconvenience of reducing the 'resolution' by not discriminating between soil microbial and plant CO_2. Results from Sweden's Sub-Arctic demonstrated that soil CO_2 emissions represented 72 to 93% of the total ecosystem CO_2 emissions (Illeris et al., 2004b). More recently, a study at Daring Lake showed that soil CO_2 emissions accounted for approximately 50% of the whole ecosystem CO_2 emissions for all three landform-vegetation units (i.e., dry heath, mesic birch, and wet sedge) (Nobrega and Grogan, 2008), suggesting that both soil and plants significantly contributed to CO_2 emissions. Therefore, it is likely that the activities (i.e., metabolisms) of both soil microbes and plants increased in a consistent way from Up, Back, to Low and from Hum to W landform units.

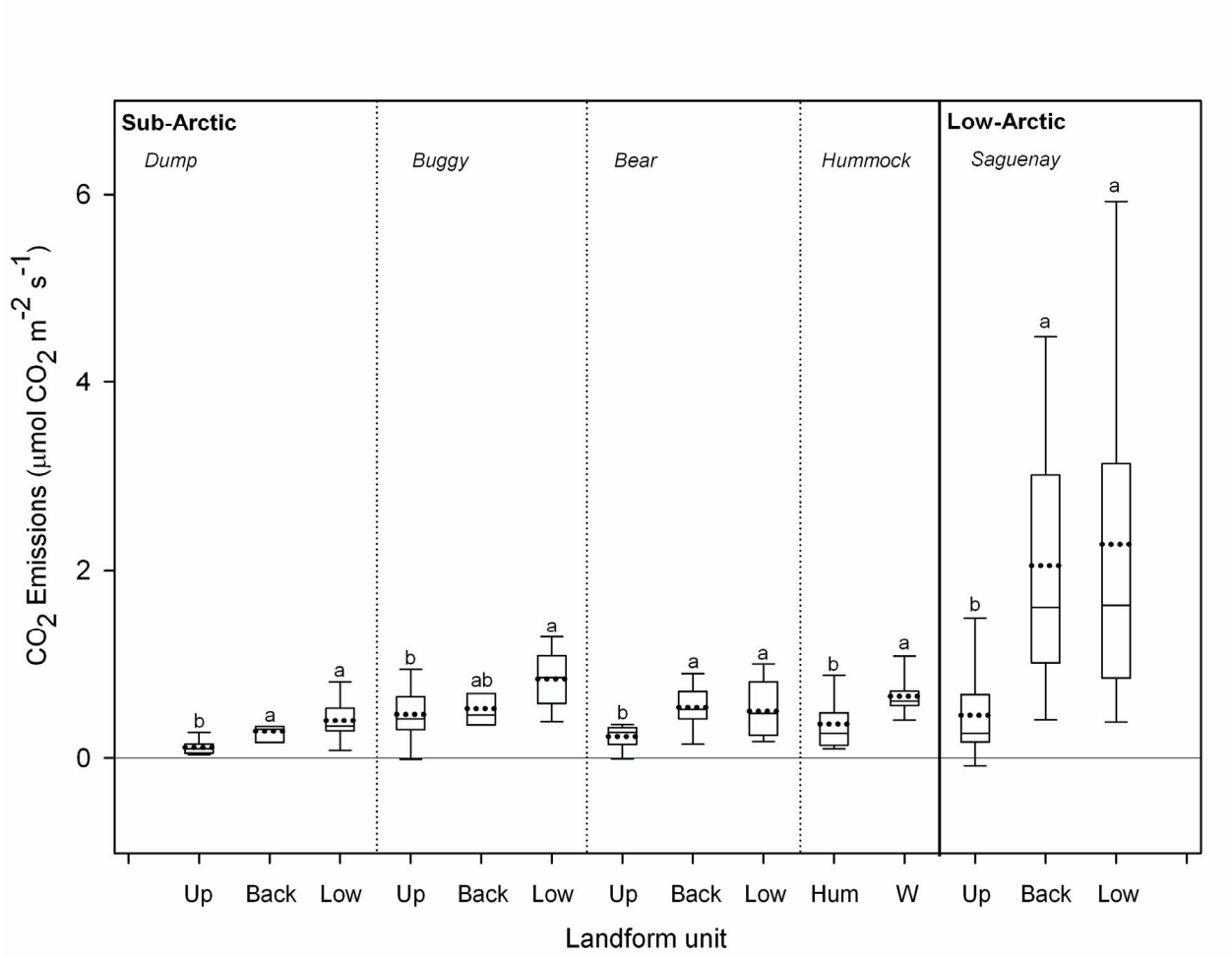


Figure 4.5: Soil CO_2 emission rates between ecosystem and site sampled for this study. The lower boundary of the box indicates the 25th percentile, the line within the box indicates the median, the dashed line in the box represents the mean, the dashed line in the box represents the mean, the upper boundary of the box indicates the 75th percentile, and the whiskers above and below the box indicate the 90th and 10th percentiles. For each site, differences between landform units were determined using one-way ANOVA and Games-Howell at a level α=.05 was used as post-hoc test (equal variances not assumed). Upper slope (Up); Back slope (Back); Lower slope (Low); Hummock (Hum); Wedge (W).

4.4.3 Ecosystem Comparisons

Topography appears to be an important factor affecting soil gross N mineralization and soil CO_2 emissions throughout the Arctic. However, these results suggest that the amplitude effect of topography on soil N and C cycling processes was not similar among the Arctic ecosystems (Table 4.2), making comparisons extremely difficult. Furthermore, the results show much more variations of GHG emissions at Daring Lake compared to Churchill. Several factors such as soil parent materials, soil forming processes (e.g., esker vs. raised beach), slope aspect, and dominant wind direction may explain the difference among sites and ecosystems (Havström et al., 1993). Furthermore, because the N and C cycling processes measured for this study represent a small time window (i.e., snap-shot measurements), temporal variations make comparisons among ecosystems difficult. In High-Arctic, Chapin (1996) showed that soil N mineralization rates vary significantly throughout the growing season. Nevertheless, the gross N mineralization values measured at Daring Lake were in the range of those measured at the same site during the same period (i.e., late-summer to early fall) (Buckeridge et al., 2010b). A recent study from Churchill sampling similar soil ecosystems showed that similar CH_4 and N_2O emissions were measured throughout years 2005 and 2006 mostly because CH_4 and N_2O emissions were very low (Churchill, 2007). At Daring Lake, Nobrega and Grogan (2008) measured significant differences in CO_2 emissions between June and September 2004. However, the CO_2 fluxes measured for this study correspond to those measured by the latter study during the same period (second week of August). Therefore, gross comparisons among ecosystems can be postulated because all ecosystems were sampled during the same biological period, two to three weeks before plant senescence.

Churchill had significantly higher N mineralization values followed by Truelove and Daring Lake (Table 4.2; Figure 4.2). Furthermore, Daring Lake had significantly higher CO_2 emissions than Churchill and no significant difference in CH_4 and N_2O emissions between both ecosystems was found (Table 4.2; Figures 4.3 to 4.5). The reason why Daring Lake had the lowest gross N mineralization values but the highest CO_2 emissions observed is not clear. A study from Northern Alaska showed that moist non-acidic tundra soils have consistently lower soil C:N values, greater microbial activity, and more highly decomposed SOM than moist acidic soils

(Walker et al., 1998). Therefore, it is possible that the combined effect of low soil pH and high soil C:N values (Table 4.3) led to low N mineralization and high CO_2 emissions (Sjögersten and Wookey, 2005). However, this explanation was not consistent with the hummock site in Churchill, which had similar pH and soil C:N as Daring Lake but higher gross N mineralization and lower CO_2 emissions. Furthermore, the hummock site in Churchill had much higher SOC than Daring Lake (Table 4.3). Since SOM characteristics strongly affect C and N mineralization in Arctic and Tundra soils (Hobbie, 1996; Nadelhoffer et al., 1991; Sjögersten and Wookey, 2005), further analyses assessing the role of SOM characteristics are needed to improve our understanding of these critical soil C and N cycling processes.

4.4.4 Changing Climate: A Landscape Perspective

4.4.4.1 Integrating N Mineralization and GHG Emissions

As stated before, Arctic soils contain a large proportion of SOC above and below the permafrost table. In some Arctic regions, soils have been accumulating C for as long ago as 11,200 yr B.P. (Tarnocai et al., 2008). In the literature, it is often suggested that global warming will increase soil N mineralization, plants that better 'consume' this N surplus (e.g., shrubs > mosses) will slowly take advantage of this situation, after which C sequestration (i.e., in soils and plants) and soil nutrient cycling processes will progressively increase (Jonasson et al., 1999; Sturm et al., 2001a; Weintraub and Schimel, 2005). For example, if the abundance, size, and coverage of Arctic shrubs increase in response to climate change, as is expected, snow-shrub interactions could cause an increase in snow depth and hence increase spring runoff, winter temperatures, and likely GHG emissions (Sturm et al., 2001b; Welker et al., 2000). Alternatively, plants could benefit from the increase of soil nutrients and offset soil C and N lost through GHG by sequestering more C in their biomass. When environmental factors such as topography do not limit plant establishment, shrubs can achieve dominance potentially within a decade, whereas spruce trees often require several decades to centuries to achieve dominance within tundra (Chapin III and Starfield, 1997; Epstein et al., 2004; Sturm et al., 2001a). For the next decades, this lag in plant establishment might determine whether or not plant biomass increases will offset SOM losses.

It is rarely discussed that, depending on topographic position, plants that better use this N surplus may not benefit from the additional supply because of the winds, temperature fluctuations, etc (Fahnestock et al., 2000; Giblin et al., 1991). Landform units with contrasting hydrology often differ dramatically in their capacity as C stores: wet areas generally act as C sinks, whereas the surrounding well-drained areas are weaker sinks or even C sources (Jones et al., 2000; McFadden et al., 2003; Sjögersten et al., 2006; Welker et al., 2000). In mountainous areas such as Alaska, topography poses a strong environmental barrier to species migration, causing a pronounced time lag in forest expansion, or even preventing expansion (Rupp et al., 2001). The soil N mineralization and CO_2 emissions measured throughout Arctic landscapes strongly suggested that landform units may respond differently to climate change. These results also agree with Nobrega and Grogan (2008) and Cheng et al. (1998) who concluded that soil C cycling responses to climate changes are likely to be highly ecosystem-specific, and thus vary substantially across Arctic landscapes. If plants are not able to establish and sufficiently grow, as expected on topographical positions that experience extreme climates such as upper slope areas, plants will not offset soil C and N lost through SOM mineralization and GHG. Therefore, landforms such as upper slope areas will have a greater time lag in shrubs and/or forest expansions or simply will not promote any plant establishment because of their limiting microclimates (Burke, 1989; Fahnestock et al., 2000). Furthermore, upper slopes are at risk to lose considerable amounts of mineralized N down slope via soil surface water (Giblin et al., 1991; Kummerow et al., 1987) and N_2O via soil emissions (Ma et al., 2007) as this study shows that all landform units from all ecosystems store considerable amounts of SOM and are biologically active. Therefore, topography should be considered when soil N and C cycling processes are evaluated and/or modelled in the Arctic. Generalizations of the climate change impact on soil N and C levels and cycling processes throughout Arctic landscapes are less certain if topography is not taken into consideration.

4.4.4.2 Soil Temperature Paradigm

Numerous studies have shown an increase in soil C and N cycling processes when soil temperatures increase (Christensen et al., 1999b; Christensen et al., 1999c; Illeris et al., 2004a; Oelbermann et al., 2008; Rinnan et al., 2008; Rodionow et al., 2006; Schmidt et al., 2002; Shaver

et al., 1998; Welker et al., 2004). However, this *in situ* study demonstrated that high N mineralization and CO_2 emission rates were associated mostly with low soil temperatures and high soil moisture (i.e., higher N mineralization and CO_2 emissions in wet and cold locations of the landscape). It has been shown that both soil microorganisms and plant roots in Arctic soils are well-adapted to low temperatures and are active even when soil temperatures are nearly 0 °C (Borner et al., 2008; Edwards and Jefferies, 2010; Pautler et al., 2010; Schimel et al., 2004; Strebel et al., 2010; Welker et al., 2004). Therefore, low temperatures measured in lower slope areas for almost all sites and ecosystems did not limit soil N mineralization and CO_2 emissions. Lower slope areas experience low summer temperatures but high winter temperatures as they tend to accumulate more snow than surrounding upper areas (Fahnestock et al., 2000). Therefore, although this study did not directly measure seasonal variations, it is possible that extreme temperature events (i.e., annual temperature fluctuations) overruled mean annual temperatures in determining N and C cycling rates. Nevertheless, I believe that the topographic position should be considered when the impact of both soil temperatures and soil temperature fluctuations on soil N and C cycling processes are studied at the landscape scale in the Arctic.

4.5 Conclusions

To my knowledge, this is the first study that simultaneously evaluated *in situ* gross N mineralization and soil GHG emissions at the landscape scale in such high-latitude environments. This study showed significant N and C cycling rates were measured on all landform units. Topography had a considerable impact on gross N mineralization rates as well as soil CO_2 emissions. For all ecosystems, both gross N mineralization and CO_2 emissions generally increase from Up, Back, to Low and from Hum to W landform units. Topography had small impact on CH_4 emission rates, whereas topography had no significant impact on N_2O emissions most likely because net emissions were extremely low. Although all N and C cycling processes represent a short time period (i.e., snap-shot measurements), comparisons among ecosystems can be postulated because all ecosystems were sampled during the same biological period (two to three weeks before plant senescence). Comparisons among ecosystems showed that Churchill (Sub-Arctic) had the highest gross N mineralization rates, whereas Daring Lake (Low-Arctic) had the highest CO_2 emission rates. Although the explanation is still unclear, these

results suggest that SOM qualities are potential factors affecting N and C cycling rates. The ability of each ecosystem to offset climate change impacts on soil C balance will likely depend upon soil topography. Areas that promote plant growth and establishment (e.g., lower slope) have high offset potential for the next decades. In contrast, areas that do not promote plants because of their harsh conditions and climates (e.g., upper slope) have low offset potential. Therefore, topography should be considered when soil N and C cycling processes are evaluated and/or modelled in the Arctic.

Chapter 5 : Organic Matter Qualities Influences Mineralization and GHG Emissions in Cryosols: A field-based Study of Sub- to High Arctic Soils

Preface

The last two chapters showed that Arctic soils store large amounts of highly labile SOM (Chapter 3) and that major C (CO_2) and N (N mineralization) cycling processes considerably vary across ecosystems and topography (Chapter 4). This section integrates previous research chapters and relates C and N processes to SOM qualities at the landscape scale. The information and findings obtained from this chapter are essential and set the conclusion of this thesis.

5.1 Abstract

Arctic soils store large amounts of highly labile soil organic matter (SOM) and several studies have suggested that SOM characteristics may explain variations of several SOM cycling rates across Arctic landscapes and Arctic ecosystems. The objective of this study was to investigate the influence of routinely measured soil properties and SOM characteristics on soil gross N mineralization and soil GHG emissions at the landscape scale. This study was carried out in three distinct Canadian Arctic ecosystems: Sub-Arctic (Churchill, MB), Low-Arctic (Daring Lake, NWT), and High-Arctic (Truelove Lowlands, NU). The landscapes were divided into five landform units: 1) upper slope (Up), 2) back slope (Back), 3) lower slope (Low), 4) hummock (Hum), and 5) wedge (W). Soil gross N mineralization was measured *in situ* using ^{15}N dilution technique, whereas soil GHG emissions (N_2O, CH_4, and CO_2) were measured *in situ* using a multicomponent Fourier transform infrared gas analyzer coupled with an automated dark chamber. Soil organic matter characteristics were determined by 1) water-extractable organic matter (WEOM), 2) density fractionation of SOM, and 3) solid-state CPMAS ^{13}C nuclear magnetic resonance (NMR) spectroscopy. Results showed that gross N mineralization, N_2O, and CO_2 emissions were affected by SOM quantity and qualities. Soil moisture, soil organic carbon (SOC), light fraction (LF) of SOM, and O-Alkyl-C to Aromatic-C ratio (OAC:AroC) positively influenced gross N mineralization, N_2O and CO_2 emissions, whereas the relative proportion of AroC negatively influenced those N and C cycling processes. Relationships between SOM characteristics and CH_4 emissions were not significant throughout all Arctic ecosystems. Furthermore, results showed that Low and W landform units store relatively more labile C than Up and Back landforms. These results are particularly important because they can be used to produce better models that evaluate SOM stocks and dynamics under several climate scenarios and across Arctic landscapes and ecosystems.

5.2 Introduction

Currently there is much interest in Arctic soils probably due to the fact that these permafrost-affected soils store approximately 60% of the organic carbon (C) in all soils of North America (Tarnocai et al., 2008). Previously, this study demonstrated that Arctic surface soils store

relatively labile soil organic matter (SOM) with a great potential for release under less harsh climate conditions (Chapter 3). All climate change scenarios predict a disproportionate temperature increase in the Arctic compared to temperate regions such as the Canadian prairies (Huntington et al., 2005). Therefore, combining large stocks of SOM, highly labile SOM, and high climate change severity could trigger a massive release of greenhouse gas (GHG) into the atmosphere – enhancing the climate change effect. However, any change in soil C and nitrogen (N) cycling rates could lead to a plant diversity shift and drastically modify the local plant and animal resource supplies. Therefore, understanding the parameters affecting Arctic SOM decomposition is crucial for both international agencies concerned with quantifying global C and GHG budgets and for northern communities (i.e., local food modifications).

In high latitudes, three major soil parameters have been as identified affecting SOM mineralization processes (e.g., N mineralization, GHG emissions, etc): 1) soil moisture, 2) soil temperature, and 3) SOM characteristics (Hobbie et al., 2000). While the effects of soil moisture and temperature are well documented (Biasi et al., 2005; Nobrega and Grogan, 2008; Schmidt et al., 2002; Welker et al., 2004), the effects of SOM characteristics on SOM mineralization are less understood. The interaction between soil GHG emissions and the characteristics of SOM in the Arctic has been discussed in the literature. For example, Grogan and Jonasson (2005) concluded that the fresh and labile SOM pools strongly and positively affected soil carbon dioxide (CO_2) emissions and hence, soil C and N cycling rates. A study from Greenland suggested that the allocation of recently fixed C to the roots affected substrate quality and then positively influenced soil methane (CH_4) emissions (Ström et al., 2003). Similarly, a recent study showed that soils with relatively labile SOM produced more CH_4 than soils containing more recalcitrant SOM (Waldrop et al., 2010). Nadelhoffer et al. (1991) concluded that the characteristics of SOM was more important than soil temperature in controlling rates of C and N mineralization processes of six Alaskan Arctic soil ecosystems. Similarly, Biasi et al. (2005) found that SOM qualities might overrule other important factors such as soil temperature and soil moisture to explain soil N mineralization and CO_2 emission rates. Although SOM characteristics are often suggested to explain soil nutrient cycling processes in the Arctic, SOM characteristic assessments are rarely conducted. In the previous chapter, it was suggested that variations in SOM qualities may explain variations in several SOM cycling processes (i.e., gross N

mineralization, N_2O emissions, and CO_2 emissions) between landform units and across Arctic ecosystems. Therefore, assessing and understanding substrate characteristics appear to be a good way to better understand variations in soil N mineralization and soil GHG emissions across Arctic landscapes and throughout Arctic ecosystems.

In order to characterize SOM characteristics, several techniques have been proposed: 1) fractionation of humic substances, 2) density fractionation of SOM, 3) characterization by chemical methods, 4) characterization by spectroscopic methods, and 5) extraction of water-extractable organic matter (WEOM) (Chantigny et al., 2008; Swift, 1996). While fractionation of humic substances and characterization by chemical methods are extremely useful in determining recalcitrant pools of SOM (e.g., organic acids and carbonyl/hydroxyl groups), density fractionation of SOM, characterization using spectroscopic methods [e.g., nuclear magnetic resonance (NMR)], and determination of WEOM are all methods that quantify labile and fresh components of SOM. In addition, because no corrosive chemicals are used to separate SOM pools, these methods are considered less "destructive" and more representative of the partly decomposed and labile molecules of SOM. Therefore, density fractionation of SOM, spectroscopic, and WEOM are the three techniques chosen to characterize Arctic SOM characteristics because Arctic soils store relatively labile SOM and soil nutrient cycling processes are of primary importance in the Arctic. **The objective of this study was to investigate the influence of soil general properties and SOM qualities on soil gross N mineralization and soil GHG emissions at the landscape scale.**

5.3 Materials and Methods

Detailed site descriptions and methodological considerations can be found elsewhere in this dissertation (Chapters 3 and 4), but are summarized below.

5.3.1 Study Locations

This study was conducted in three Arctic ecosystems: Sub-Arctic (Churchill, MB), Low-Arctic (Daring Lake, NWT), and High-Arctic (Truelove, NU). Truelove and Daring Lake were sampled in 2008 and Churchill was sampled in 2009. All sites were sampled at the end of their growing

seasons (i.e., from two to three weeks before plant senescence). Between 1996 and 2006, the Churchill continental climate had a mean annual air temperature of -5.8 °C and a mean annual precipitation of 501 mm (Environment Canada, 2011). Daring Lake is located 300 km northeast of Yellowknife, Canada. Seven-year climate records indicated a mean annual air temperature of -9.0 °C (Nobrega and Grogan, 2008). Truelove is located on the northeast coast of Devon Island, Canada. Between 1996 and 2006, a permanent weather station installed at Grise Fiord, Canada (~80 km north of Truelove) measured a mean annual air temperature of -14.2 °C and a mean annual precipitation of 184 mm (Environment Canada, 2011).

5.3.2 Method of Sampling

On each site, the sampling locations were evenly distributed among upper (Up), back (Back), and lower (Low) slopes for catena sites and between hummock (Hum) and wedge (W) for hummock sites. A minimum sample spacing of 5 m was used between sampling points. The sampling area for each sampling point covered 0.3 m^2. The first day, soil temperature (T) was determined in the field during GHG measurements. The second day, soil gross N mineralization incubation was started, soil samples were collected, and a sub-sample was immediately extracted for WEOM.

5.3.3 Soil General Analysis

Soil gravimetric water content (moisture) was calculated using weight loss (105 ^{o}C for 24 h). Soil pH was measured in 0.01 *M* $CaCl_2$. Soil organic carbon (SOC) and total nitrogen (TN) were evaluated by dry combustion (C632 and Leco-2000, Leco Corporation, St. Joseph, MI) after removing carbonates with an acid solution (6% H_2SO_3).

5.3.4 Soil N Mineralization

Soil gross N mineralization was determined using the ^{15}N isotope dilution technique (Davidson et al., 1991; Hart et al., 1994a). Two intact soil cores per sampling location were injected with a solution of ^{15}N-NH_4^+. One core was extracted immediately in 2 *M* KCl and the other was incubated for 24-h *in situ* before extraction. The ^{15}N-NH_4^+ concentrations in KCl extracts were then used to calculate gross N mineralization following Hart et al. (1994a).

5.3.5 Soil GHG Emissions

The greenhouse gas (GHG) measurements were measured at Churchill and Daring Lake using a multicomponent Fourier transform infrared gas analyzer (Gasmet DX-4015, Gasmet Technology, La Prairie, QC) coupled with an automated dark chamber (model 8100-104, Li-Cor Biosciences, Lincoln, NE) (Lamb et al., 2011). During measurement, the chamber was closed 5 min and the gas concentration integrated over a 30-s interval at Daring Lake and a 20-s interval at Churchill. The first derivative of gas concentration (ppm) and time (s) was taken to estimate the gas fluxes.

5.3.6 Soil Organic Matter Characteristics

5.3.6.1 Water-Extractable Organic Matter

Water-extractable organic matter (WEOM) was determined following the procedure of Chantigny et al. (2008). All samples were extracted on site, incubated *in situ* for 24 h, and then analyzed for water-soluble organic carbon (WSOC) and water-soluble organic nitrogen (WSON) by oxidation and chemiluminescence (TOC-V and TNM-1 Measurement Unit, Shimadzu Scientific Instruments, Kyoto, Japan), and colorimetry (SmartChem 200 Discrete Autoanalyzer, Westco Scientific, Brookfield, CT).

5.3.6.2 Soil Organic Matter Density Fractions

The light and heavy fractions (LF and HF) of soil organic matter were separated in sodium iodide (NaI) with a specific density adjusted at 1.55 g mL^{-1} (Paré and Bedard-Haughn, 2011). The organic C of the LF (C-LF) and HF (C-HF), as well as total N (N-LF; N-HF) contents were determined by dry combustion as described above.

5.3.6.3 Solid-State CPMAS ^{13}C NMR

The relative proportions of Alkyl-C (AC), O-Alkyl-C (OAC), Carbohydrates-C (CC), Methoxyl-C (MC), Aromatic-C (AroC), and Carbonyl-C (CbyC) in SOM were evaluated using solid-state CPMAS ^{13}C nuclear magnetic resonance (NMR) spectroscopy at the Canada Plant Biotechnology Institute in Saskatoon.

5.3.7 Statistical Analysis

Variance homogeneity was evaluated with the Levene test. Data were transformed (i.e., logarithm or exponential) when they were not normally distributed. Relationships between soil properties, SOM quality parameters, gross N mineralization, and GHG emissions were first examined using the Pearson correlation procedure in SPSS version 13 for Windows (SPSS Inc., 2004) (Table 5.1). Because all measured parameters correlated with each other (i.e., collinearity), multivariate techniques are uniquely well-suited for reducing the variance of measured soil parameters into independent axes, clarifying the relationship among SOM qualities, N mineralization, and GHG emissions at the landscape scale. The variances of soil parameters (25 variables) were condensed into two axes using Principal Component Analysis (PCA) procedure in PC-ORD version 5.10 for Windows (McCune and Mefford, 2006) and transformed data. Correlation was used for cross-products matrix and the distance-based biplot was selected to calculate scores for variables. In order to put each variable on equal footing with each other, the normalization of the data was done by calculating standardized values (i.e., Z scores) by using the mean and standard deviation of each variable (Shaw, 2003). Because the first two axes explained most of the variance (>55%) (Table 5.2), only axes 1 and 2 were used for further analysis. Linear relationships among data were assumed (Appendix E). Results from PCA (i.e., axis scores and vectors) were plotted in a bubble plot where the bubble sizes represent the relative ecosystem value (not transformed) of the measured process (i.e., gross N mineralization or GHG emissions). Plots were computed in SigmaPlot version 11.0 for Windows. High vector length (i.e., eigenvector loading) means high contribution of the property to the axis. In order to reduce plot complexity, only key vectors (i.e., properties with high eigenvector loadings) are shown on figures. However, readers may refer to the eigenvector loadings table (Table 5.3) for all results. There is no formal test of significance available to decide whether any given individual variables contribute significantly to PCA axes (Shaw, 2003). Proximities among vectors suggest similitude among properties. Correlation (Pearson) between PCA result (axis 1 and axis 2) and the measured processes (i.e., gross N mineralization or GHG emissions) were measured as above. Inferential statistic may be applied to ordination data (Shaw, 2003) because: 1) the measured processes were not used in ordination and 2) axes generated by PCA ordination were independent and meet ANOVA assumptions (i.e., normality and variance homogeneity).

Table 5.1: Correlation coefficients (Pearson) between soil parameters and soil gross N mineralization (N min), soil carbon dioxide emission (CO_2), soil methane emission (CH_4), and soil nitrous oxide emission (N_2O).

Soil Parameter	N min	CO_2	CH_4	N_2O	N min	CO_2	CH_4	N_2O	N min
	---------- Churchill ----------				---------- Daring Lake ----------				Truelove
General Properties									
T	-0.57	-0.09	-0.21	-0.23	-0.03	-0.17	0.39	-0.11	-0.07
Moist	0.65	0.31	0.27	0.19	0.28	0.43	-0.08	0.29	0.48
pH	0.08	0.14	-0.07	-0.07	-0.17	-0.26	0.26	0.02	0.00
SOC	0.59	0.16	0.18	0.21	0.36	0.43	-0.16	0.14	0.52
TN	0.64	0.23	0.08	0.15	0.41	0.43	-0.17	0.11	0.37
Soil C:N	-0.09	-0.19	0.32	0.21	-0.20	-0.02	-0.04	0.05	0.11
Water-Extractable Organic Matter									
WSOC	0.74	0.29	0.05	0.14	0.20	0.31	-0.14	0.04	0.25
WSON	0.57	0.32	0.12	0.02	0.25	0.22	-0.13	-0.01	0.26
WEOM C:N	0.21	0.19	0.01	0.05	-0.14	0.07	-0.04	0.23	-0.37
Organic Matter Density Fractions									
LF Qty	0.52	0.20	0.15	0.23	0.40	0.45	-0.13	0.24	0.29
C-LF	0.51	0.17	0.16	0.25	0.40	0.47	-0.14	0.22	0.29
N-LF	0.53	0.21	0.13	0.21	0.43	0.46	-0.14	0.22	0.30
LF C:N	-0.18	-0.05	0.04	0.08	-0.41	-0.07	0.09	0.18	-0.13
C-HF	0.64	0.19	0.20	0.19	0.22	0.40	-0.18	0.08	0.21
N-HF	0.66	0.26	0.17	0.18	0.24	0.32	-0.12	-0.01	0.06
HF C:N	0.64	0.18	0.21	0.19	0.22	0.41	-0.19	0.07	0.45
Solid-state CPMAS ^{13}C NMR spectroscopy									
AC	-0.11	-0.10	-0.09	-0.10	-0.13	-0.04	-0.12	-0.19	-0.16
OAC	0.37	0.31	0.29	0.18	0.26	0.40	-0.18	0.23	0.64
CC	0.29	0.30	0.25	0.16	0.24	0.40	-0.20	0.22	0.64
MC	0.05	0.06	0.06	-0.05	-0.12	0.04	-0.16	-0.06	-0.06
AroC	-0.26	-0.30	-0.21	-0.10	-0.34	-0.46	0.29	-0.16	-0.31
CbyC	-0.24	-0.16	-0.19	-0.15	-0.15	-0.23	-0.16	-0.09	-0.08
CC:MC	0.07	0.07	0.06	0.11	0.20	0.27	-0.08	0.16	0.26
OAC:AroC	0.30	0.31	0.24	0.12	0.30	0.45	-0.28	0.18	0.34
OAC:AC	0.27	0.23	0.20	0.16	0.22	0.29	-0.07	0.27	0.34

Temperature (T); moisture (Moist); soil organic carbon (SOC); light fraction (LF); heavy fraction (HF); Alkyl-C (AC); O-Alkyl-C (OAC); carbohydrates-C (CC); methoxyl-C (MC); aromatic-C (AroC); carbonyl-C (CbyC); Water-soluble organic carbon (WSOC) and nitrogen (WSON).

Table 5.2: Eigenvalues and percentage of variance explained by principal components analysis (PCA).

	Sub-Arctic (Churchill)			Low-Arctic (Daring Lake)			High-Arctic (Truelove)		
	Eigenvalue	% Variance	Cumulative variance	Eigenvalue	% Variance	Cumulative variance	Eigenvalue	% Variance	Cumulative variance
Axis 1	12.96	51.83	51.83	14.47	57.89	57.89	9.35	37.38	37.38
Axis 2	4.12	16.49	68.32	3.94	15.76	73.65	4.39	17.57	54.95
Axis 3	1.88	7.53	75.86	1.96	7.98	81.63	3.39	13.55	68.49
Axis 4	1.42	5.69	81.55	1.41	5.63	87.25	3.19	12.75	81.24
Axis 5	1.27	5.09	86.64	0.96	3.83	91.09	1.14	4.54	85.78
Axis 6	0.73	2.93	89.57	0.54	2.15	93.24	0.82	3.27	89.05
Axis 7	0.67	2.70	92.26	0.41	1.65	94.89	0.67	2.67	91.72

Table 5.3: Eigenvector loadings for each soil parameters used for principal components analysis (PCA).

Parameters	Sub-Arctic (Churchill)		Low-Arctic (Daring Lake)		High-Arctic (Truelove)	
	Axis 1	Axis 2	Axis 1	Axis 2	Axis 1	Axis 2
Temperature	1.32	-0.66	0.24	-0.12	-0.11	-0.18
Moisture	-1.77	0.74	-1.23	0.13	0.60	-0.23
pH	1.11	1.34	1.16	-0.03	-1.83	2.28
SOC	-1.87	0.59	-1.28	0.47	2.88	-1.70
Soil TN	-1.68	1.52	-1.19	1.01	1.67	-3.19
Soil C:N	-0.53	-2.53	-0.44	-2.16	2.81	1.05
WSOC	-1.36	0.94	-1.26	-0.13	2.38	-1.96
WEOM C:N	-0.87	-1.19	-0.56	-1.42	-1.46	-0.11
LF Qty	-1.86	0.29	-1.28	0.16	2.85	-0.93
C-LF	-1.86	0.29	-1.27	0.29	2.73	-1.12
N-LF	-1.77	0.86	-1.26	0.39	2.71	-1.27
LF C:N	-0.08	-2.82	-0.04	-2.12	0.49	3.21
HF Qty	1.84	-0.58	1.27	-0.13	-2.86	0.77
C-HF	-1.57	1.27	-0.96	1.36	0.07	-3.13
N-HF	-1.53	1.79	-0.61	1.97	-0.80	-3.57
HF C:N	0.82	-2.09	-0.86	-1.66	2.38	2.20
AC	0.50	1.58	0.43	1.31	-1.58	-3.58
OAC	-1.73	-1.01	-1.25	-0.29	2.63	1.14
CC	-1.65	-1.38	-1.26	-0.35	2.89	0.80
MC	0.77	1.99	0.08	0.71	-2.48	-1.04
AroC	1.40	0.53	1.15	-0.48	-0.95	3.11
CbyC	1.30	0.41	0.96	0.09	0.27	1.26
CC:MC	-1.25	-2.15	-0.91	-0.84	2.99	1.21
OAC:AroC	-1.52	-0.61	-1.23	0.28	1.58	-2.23
OAC:AC	-2.54	-1.03	-1.04	-0.91	2.17	3.22

Soil organic carbon (SOC); total nitrogen (TN); Water soluble organic carbon (WSOC); Water extractable organic matter (WEOM); Light fraction quantity (LF Qty); Heavy fraction (HF); Alkyl-C (AC); O-Alkyl-C (OAC); Carbohydrates-C (CC); Methoxyl-C (MC); Aromatic-C (AroC); Carbonyl-C (CbyC).

5.4 Results and Discussion

5.4.1 Soil Organic Matter Quantity and Quality Distributions across the Landscapes

Topography (i.e., landform units) had a strong impact on soil properties and SOM characteristics (Figure 5.1). Soils with high moisture, high SOM content, and highly labile SOM occur on Low and W landform units, whereas drier soils that store less SOM, but more recalcitrant SOM, were found on Back and Low landform units (Figure 5.1). However, the effect of the topography on SOM qualities varied among ecosystems: Truelove soils were relatively more homogenous among landforms compared to the other two ecosystems (Figure 5.1).

Redistribution of water from Up slope to Low slope and from Hum to W may explain why Low and W landform units were associated with moist soil conditions. Furthermore, better microclimates that experience Low areas comparatively to Up and Back areas promote plant growth and hence may explain why higher SOM content was found on this landform. However, the explanation why more labile SOM was found on Low landform comparatively to Up and Back is equivocal. Some authors have suggested that low temperature as well as high soil moisture may limit microbial decomposition of SOM and hence may promote the accumulation of labile SOM (Hobbie et al., 2000; Weintraub and Schimel, 2005). Alternatively, it is possible that conditions found on Low landform lead to high SOM decomposition (i.e., high N and C cycling), enhance plant growth, and hence increase the fresh and labile SOM input from plants. Because higher N and C cycling rates were measured on Low and W landforms that had high moisture contents (Chapter 5), this study agrees most with the latter explanation.

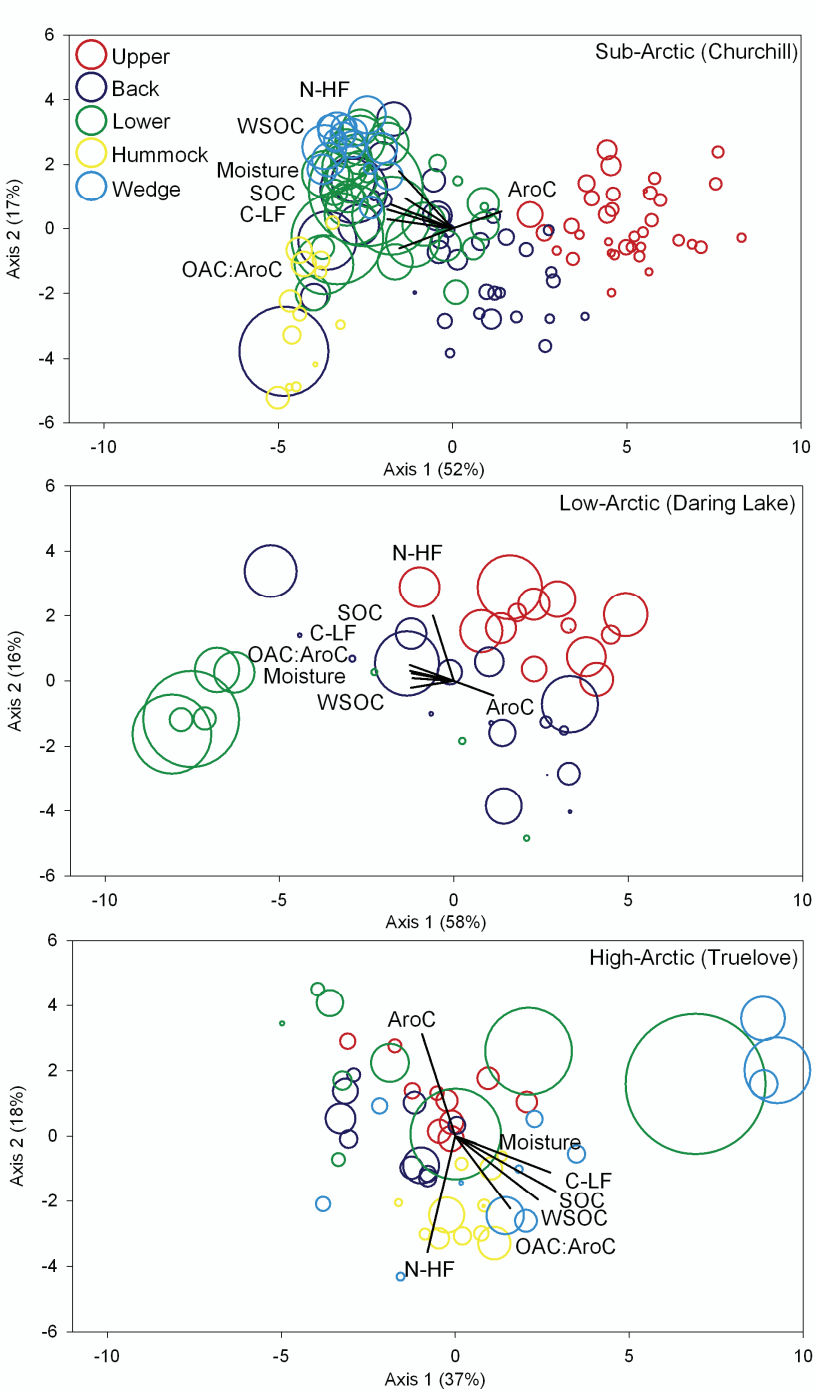


Figure 5.1: Principal component analysis (PCA) of all measured soil parameters (25 variables). All variable were transformed to meet normality before PCA (logarithm or exponential). PCA results are categorized by topographical position (colors). The bubble sizes represent the relative values of gross N mineralization rates (not transformed). Only selected vectors are shown. All vector coordinates are shown on Table 5.3. Aromatic-C (AroC); heavy fraction (HF); light fraction (LF); O-Alkyl-C (OAC); soil organic carbon (SOC); water-soluble organic carbon (WSOC).

5.4.2 The Influence of Soil Parameters on Soil N Gross Mineralization

For all ecosystems, soil containing high stocks and labile SOM had higher gross N mineralization rates (Table 5.4). At Churchill, the results show a strong and clear association between high gross N mineralization rates, soil moisture, SOM stock (SOC), and SOM characteristics (e.g., C-LF, WEOC, AroC, and OAC:AroC) (Figure 5.1). Alternatively, Daring Lake and Truelove had less-clear association between gross N mineralization rates, soil moisture, SOM stock, and SOM characteristics. Consequently, axes 1 and 2, which represent about 65% of the variance of the 25 measured variables, explained 45, 14, and 22% of gross N mineralization rates for Churchill, Daring Lake, and Truelove, respectively (Table 5.2).

In Arctic terrestrial ecosystems, soil moisture generally has a positive effect on soil N mineralization (Figure 5.1). In High-Arctic (i.e., Svalbard) and Sub-Arctic (i.e., northern Sweden) soils, several consecutive years of increasing soil moisture significantly enhanced SOM decomposition and mineralization (Robinson et al., 1995). In northeast Greenland, adding water to the soil significantly increased microbial biomass as well as SOM decomposition (Illeris et al., 2003) because soil microbial activity generally increases with soil moisture (Biasi et al., 2005; Söderström, 1979). Laboratory incubations demonstrated that N mineralization potential of a Low-Arctic soil gradually increased along a soil moisture gradient (Chu and Grogan, 2010). Similarly, studies from the Sub-Arctic in Sweden showed that annual *in situ* N availability increased with soil moisture (Weih, 1998) and both plant and SOM contained more nutrients from dry to moist tundra areas (Jonasson, 1983). Therefore, for most terrestrial Arctic ecosystems sampled during this study, moist soils tended to have greater N mineralization rates compared to drier soils.

The positive association of gross N mineralization rates and several labile SOM parameters (e.g., C-LF, WEOC, AroC, and OAC:AroC) and the negative association of recalcitrant parameter (e.g., AroC) suggests that, as in temperate soil ecosystems (Hart et al., 1994b), characteristics of SOM in the Arctic also influences soil N cycling.

Table 5.4: Correlation and predicted models between gross N mineralization, GHG emissions (N_2O, CH_4, and CO_2), and variances (axis 1 and axis 2) determined using principal component analysis.

Ecosystem (location)	Correlation (Pearson)		Model †		
Predicted variable	Axis 1	Axis 2	F value	*P*	R^2
Sub-Arctic (Churchill)					
N mineralization ¶	-0.55***	0.39***	55.142	<0.001	0.45
N_2O emission	-0.19*	-0.06	4.043	0.047	0.03
CH_4 emission	-0.18	-0.07			
CO_2 emission §	-0.30**	0.13	6.391	0.002	0.09
Low-Arctic (Daring Lake)					
N mineralization ¶	-0.26	0.34*	4.232	0.022	0.14
N_2O emission	-0.12	0.03			
CH_4 emission	0.18	-0.11			
CO_2 emission §	-0.30*	-0.15	4.131	0.048	0.07
High-Arctic (Truelove)					
N mineralization ¶	0.43**	0.25	8.199	0.001	0.22

Significant at levels *: $P < .05$; **: $P < .01$; ***: $P < .001$; non-significant (NS) correlation. † Linear regression model: predicted variable = Axis 1 + Axis 2 + intercept. Exponential (¶) or logarithm (§) transformations applied to meet normality. Refer to the eigenvector loading values (Table 5.2) to see how each individual soil parameters influence axes 1 and 2.

A positive association between the quantity of SOM and N mineralization has been previously observed in Daring Lake (Chu and Grogan, 2010), Siberia (Biasi et al., 2005), and in more temperate soil ecosystems (Accoe et al., 2004; Barrett and Burke, 2000). A recent study using Daring Lake soils showed that soil microorganisms mineralized the most labile C first and then another microbial population used recalcitrant C thereafter (Oelbermann et al., 2008). The results from this study are also consistent with Nadelhoffer et al. (1991) who found that, under field moisture and temperature ranges, SOM characteristics were significant factors affecting soil N mineralization of Arctic soils. Therefore, for all ecosystems sampled in this study, both SOM quantity and characteristics had a significant impact on soil gross N mineralization rates measured *in situ*. Soils containing relatively labile SOM had higher gross N mineralization rates.

5.4.3 The Influence of Soil Parameters on Soil GHG Emissions

5.4.3.1 N_2O Emissions

At Daring Lake, no significant association between the measured variables and N_2O emissions were observed (Table 5.4). At Churchill, the results show that moist soil containing high stocks and labile SOM tended to have high N_2O emissions (Table 5.4). However, as reflected by R^2 value, soil N_2O emissions were difficult to explain most likely because extremely low N_2O emissions were measured throughout ecosystems and landscapes (Chapter 4). Because N_2O emissions tended to be associated with moist soils having high levels and relatively labile SOM, these results suggest that denitrification was an active pathway of N_2O emissions (Wrage et al., 2001). However, Ma et al. (2007) and Siciliano et al. (2009) demonstrated recently that nitrification also produce N_2O from Arctic soils. Therefore, both nitrification and denitrification may be active in Arctic soils. However, the relative importance of these two pathways (i.e., nitrification and denitrification) in Arctic soils cannot be tested without isotope and/or acetylene reduction techniques.

To my knowledge, this is the first Arctic *in situ* study that demonstrated the positive effect of soil moisture on N_2O emissions, suggesting that, as well-established for more temperate ecosystems (Pennock et al., 1992; Rochette et al., 2010; Smith et al., 2008; Van Kessel et al., 1993; Yates et al., 2006), N_2O emissions from Arctic soils can also be affected by soil moisture.

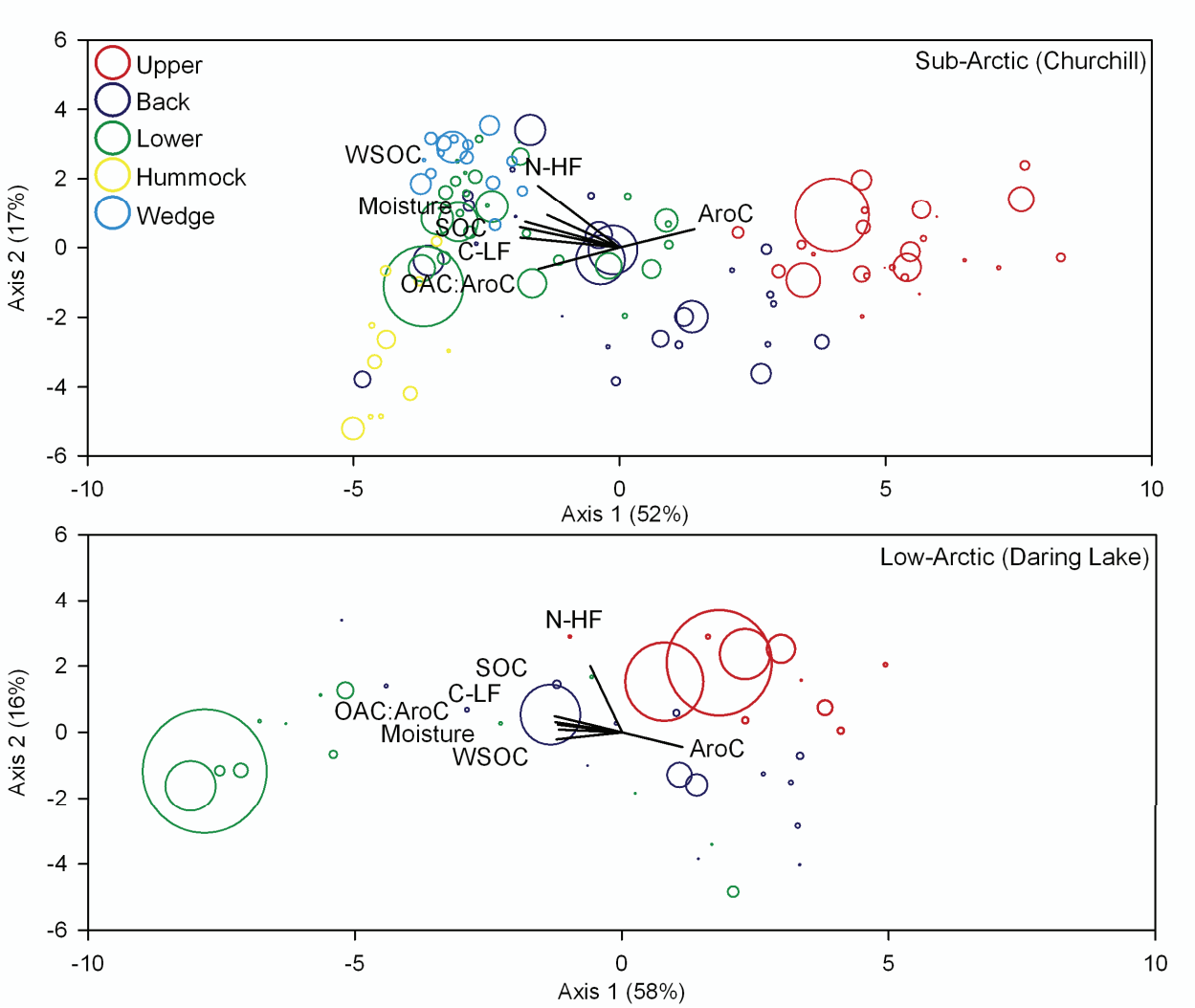


Figure 5.2: Principal component analysis (PCA) of all measured soil parameters (25 variables). All variable were transformed to meet normality before PCA (logarithm or exponential). PCA results are categorized by topographical position (colors). The bubble sizes represent the relative values of N_2O emission rates (not transformed). Only selected vectors are shown. All vector coordinates are shown on Table 5.3. Aromatic-C (AroC); heavy fraction (HF); light fraction (LF); O-Alkyl-C (OAC); soil organic carbon (SOC); water-soluble organic carbon (WSOC).

High soil moisture results in greater water-filled pore space, which directly decreases the level of oxygen transfer from air to soil, and then indirectly enhances the activity of denitrifying soil microbes. However, as Siciliano et al. (2009) suggested, denitrification in the Arctic is perhaps not as sensitive to water content as might be the case in other ecosystems that produce more N_2O – as reflected by low correlation values as well as low model R^2 value (Table 5.4). As suggested previously (Chapter 4), low N_2O emissions measured throughout ecosystems and landforms may explain low correlation to soil water content.

In the Arctic and more temperate soil ecosystems, SOM quantity and characteristics may affect its decomposition and hence, soil N cycling processes such as N_2O emissions. However, before our study, relations between N_2O emissions and SOM had not been investigated in Arctic ecosystems. In a Brazilian tropical forest, it was demonstrated that labile C (e.g., carbohydrates) enhanced denitrification (Garcia-Montiel et al., 2003; Nobre et al., 2001), which supports our association between labile C (e.g., CC, OAC:AroC) and N_2O emissions (Table 5.4). Labile C can affect soil denitrification in two ways: 1) denitrifying soil microbes use labile forms of C as an energy source in the production of N_2O and 2) as heterotrophic soil microbes use labile forms of C for their own metabolism, their oxygen demand creates anaerobic soil microsites, which then locally supports denitrifying soil microbes (Garcia-Montiel et al., 2003). Heterogeneity of soil material (e.g, rock, sand, silt, and clay), cryoturbation, and frozen pockets are all conditions that may promote and enhance microsites in Arctic soils.

Other soil parameters such as inorganic N content have been shown to affect N_2O emissions from terrestrial ecosystems. Although environmental conditions in the Arctic may be favourable for N_2O emissions (e.g., wet soils storing high stock of labile C), generally low soil inorganic N in Arctic soils limits and restricts N_2O emissions (Buckeridge et al., 2010a). In the Arctic, adding organic substrate had little effect on N_2O emissions, whereas adding inorganic N significantly increased N_2O emissions (Buckeridge et al., 2010a; Christensen, 1999). The reason for this is still unclear, but a recent study using soils from Truelove showed that N_2O emission potential strongly decreased when fungi in soil were active most likely because fungi competed for soil inorganic N against soil microorganisms responsible for N_2O emissions (Siciliano et al., 2009). Nevertheless, poor correlations between N_2O emissions and gross N mineralization rates

(Churchill: r=0.218, *P*=0.022; Daring Lake: r=0.012, *P*=0.943) suggested that N_2O emissions and soil N mineralization are not controlled by the same soil parameters. Furthermore, these poor correlations reflect the complexity of Arctic ecosystems.

5.4.3.2 CH_4 Emissions

No significant correlation between CH_4 emissions, axis 1, and axis 2 (Table 5.4) for all ecosystems suggests that our measured variables (e.g., temperature, moisture, and SOM qualities) did not explain the CH_4 emissions for both ecosystems. Low CH_4 emissions measured throughout our Arctic landscapes (Chapter 4) may explain this lack of significance. Furthermore, it is possible that other environmental parameters not measured in this study, such as soil oxygen content and climatic conditions, dominantly explained CH_4 variations.

Although statistically not significant [i.e., no significant linear model between CH_4, axis 1, and axis 2 (Table 5.4)], multivariate analyses showed an interesting trend. Regardless of the landform unit, very high CH_4 emissions (i.e., hotspots) were mostly associated with soil AroC content (Figure 5.3), which represents the recalcitrant and more stable fraction of SOM. This finding may *à-priori* be in contradiction with other studies that showed that CH_4 emissions were enhanced with labile SOM (Joabsson and Christensen, 2001; Ström et al., 2003; Waldrop et al., 2010). However, most studies of Arctic CH_4 emissions have focused on organic-dominated soils (e.g., bogs, fens, marshes, etc.), whereas our study mainly focused on mineral-dominated soils. Therefore, assessing the role of multiple C pools and their effect on methanogens (soil microbes that produce methane) and methane oxidizers (soil microbes that consume methane) might provide insights for a better understanding of CH_4 emissions from Arctic soils.

It is well-known that N in soil may also influence methane oxidizer activities (Crill et al., 1994; Schnell and King, 1994; Steudler et al., 1989). Laboratory studies using Sub-Arctic soils demonstrated that CH_4 consumption was strongly inhibited by inorganic and organic N additions (Adamsen and King, 1993; Christensen et al., 1999a). Therefore, soil N processes and pools should influence CH_4 emissions. However, the lack of a significant correlation between gross N mineralization and CH_4 emissions (Churchill: r=0.067, *P*=0.490; Daring Lake: r=0.155, *P*=0.339) does not support this hypothesis.

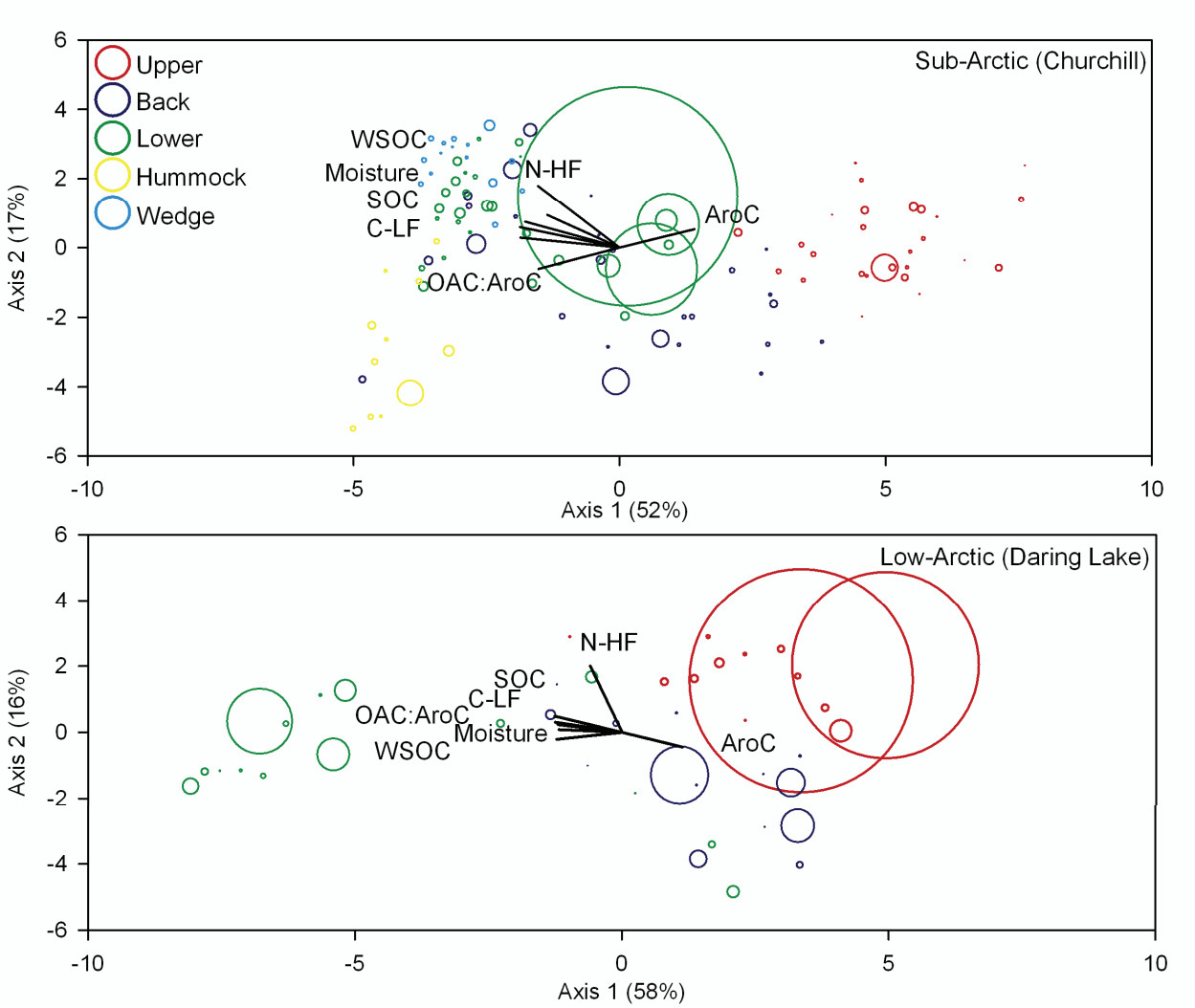


Figure 5.3: Principal component analysis (PCA) of all measured soil parameters (25 variables). All variable were transformed to meet normality before PCA (logarithm or exponential). PCA results are categorized by topographical position (colors). The bubble sizes represent the relative values of CH_4 emission rates (not transformed). Only selected vectors are shown. All vector coordinates are shown on Table 5.3. Aromatic-C (AroC); heavy fraction (HF); light fraction (LF); O-Alkyl-C (OAC); soil organic carbon (SOC); water-soluble organic carbon (WSOC).

Furthermore, a study from northern Sweden showed that adding inorganic N for seven years significantly increased CH_4 consumption, and hence potentially decreased CH_4 emissions (Christensen et al., 1997). As Crill et al. (1994) concluded, *in situ* validations are not simply dependent upon N, and other factors possibly overruled methane oxidizer activities. Finally, these contradictory results reflect the difficulty of transposing laboratory findings to the field.

5.4.3.3 CO_2 Emissions

For all ecosystems, the results show that wet soils storing large amounts of SOM and highly labile C had high CO_2 emissions rates (Table 5.4). Inversely, dry soils located on upper areas of the landscape and storing recalcitrant C (AroC) tended to have low CO_2 fluxes (Table 5.4). However, the measured variables do not well-explained CO_2 flux variations: axes 1 and 2 extracted from the 25 measured variables explained 9 and 7% of the CO_2 emissions of Churchill and Daring Lake, respectively (Table 5.4). Other variables not considered for this study (e.g., soil microbial biomass, weather, etc) may also explain variations in CO_2 emissions.

In Arctic terrestrial ecosystems, soil moisture generally has a positive effect on soil CO_2 emissions. For example, water addition increased CO_2 emissions and soil microbial activities in northeast Greenland (Illeris et al., 2003) and Antarctica (Burkins et al., 2001), suggesting that soil nutrient cycling processes are water-limited in such soil environments. Similarly to this study, Sjögersten et al. (2006) measured an increase of CO_2 emissions along a soil moisture gradient in Svalbard. However, it was demonstrated that soil moisture increased soil CO_2 emissions to a certain extent and then, when soil moisture gets extremely high, anaerobic condition processes take over and low SOM decomposition rates are measured (Christensen et al., 1999c; Giblin et al., 1991; Illeris et al., 2004a). Nevertheless, this study showed a positive influences of soil moisture on CO_2 emissions because a great majority of the sampling locations were situated in relatively dry soil areas (i.e., not flooded soil areas) and generally below the optimal moisture for SOM decomposition (Hobbie et al., 2000). In the Arctic, and in more temperate soil ecosystems, SOM quantity generally affects soil CO_2 emissions. For Arctic terrestrial ecosystems, modelling demonstrated SOM content as a spatial control on CO_2 emissions (Ostendorf, 1996). In Antarctica, the addition of C significantly increased CO_2 emissions to a greater extent than moisture and temperature increases (Burkins et al., 2001).

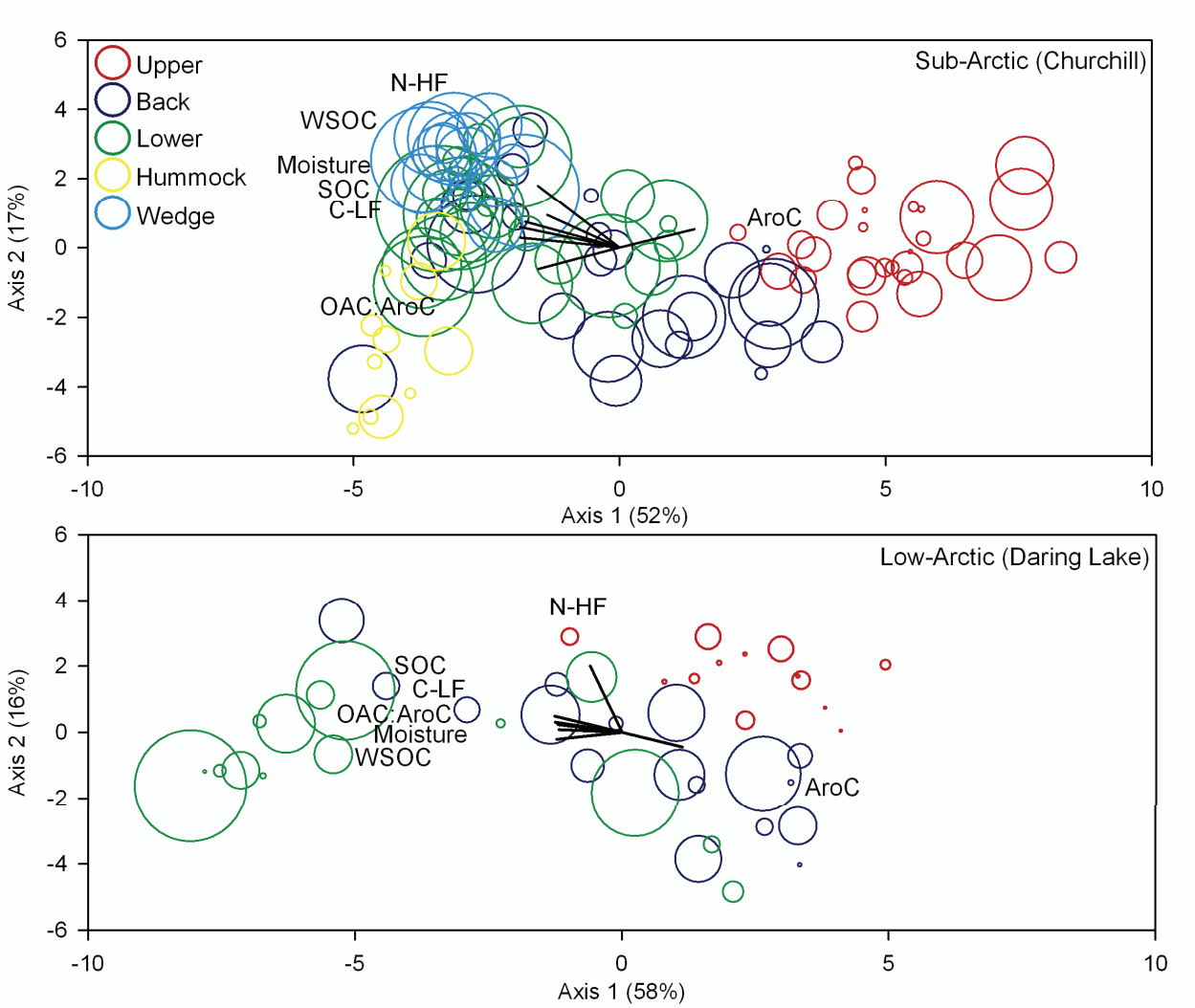


Figure 5.4: Principal component analysis (PCA) of all measured soil parameters (25 variables). All variable were transformed to meet normality before PCA (logarithm or exponential). PCA results are categorized by topographical position (colors). The bubble sizes represent the relative values of CO_2 emission rates (not transformed). Only selected vectors are shown. All vector coordinates are shown on Table 5.3. Aromatic-C (AroC); heavy fraction (HF); light fraction (LF); O-Alkyl-C (OAC); soil organic carbon (SOC); water-soluble organic carbon (WSOC).

A positive association between CO_2 emissions and WEOM was observed in northern Alaska by Neff and Hooper (2002), suggesting that soil microbes responsible for SOM mineralization most likely used WEOM (e.g., C-WEOM and N-WEOM) for their metabolism. However, the positive influences of several solid SOM quality parameters suggested that WEOM is not the only C pool that influenced CO_2 emissions from Arctic soils. The results showed a negative association between AroC content and CO_2 emissions (Table 5.4). In the Arctic, soil CO_2 emissions can be limited by the proportion of recalcitrant C (Christensen et al., 1999c; Hobbie et al., 2000). This study supports conclusions from Nadelhoffer et al. (1991) and Hobbie (1996) who found that, under field moisture and temperature ranges, SOM qualities have a substantial effect on soil C mineralization processes (e.g., CO_2 emissions).

Arctic soils are generally depleted in mineral N and any change in soil N cycling processes has the potential to affect heterotrophic soil microbes and hence processes related to C cycling. A significant positive correlation between soil gross N mineralization and CO_2 emissions was observed in Churchill ($r=0.301$, $P=0.001$) but not at Daring Lake ($r=0.120$, $P=0.461$), suggesting that soil mineral N may play a role in CO_2 emissions from Arctic soils. In Sub- and High-Arctic, *in situ* fertilization (N, P, and K) increased SOM decomposition to a greater extent than soil temperature (Robinson et al., 1995). For a wet sedge tundra in northern Alaska, six years of *in situ* fertilization (N and P) significantly increased CO_2 emissions by 2- to 4-fold (Johnson et al., 2000; Shaver et al., 1998). Similarly, results from northern Sweden showed that several years of *in situ* soil fertilization (i.e., N, P, and K) increased soil CO_2 emissions to a greater extent than soil temperature, most likely because fertilization changed both SOM characteristics and microbial activities (Christensen et al., 1997; Illeris et al., 2004b). Furthermore, a long-term fertilization experiment in Alaska showed that increasing fertilization reduced the volume of soil thaw by ~30% during summers and significantly decreased cumulative degree-days (i.e., soil temperatures) by ~40% (Johnson et al., 2000). This change in the soil thermal regime was caused by higher SOM contents at the surface, as well as shading effects due to plant cover increases. Therefore, although factors are mostly indirect, nutrient status in Arctic soils can strongly modify soil environment as well as C cycling processes.

5.5 Conclusions

This is the first study to clearly show how SOM characteristics vary across Arctic landscapes. Low soils store high stock of highly labile C, whereas Up soils store more humified SOM. Furthermore, it is the first to simultaneously investigate the influence of SOM characteristics on *in situ* gross N mineralization and soil GHG emissions at the landscape scale in such high-latitude environments. The results showed that N mineralization, N_2O, and CO_2 emissions are affected by SOM quantity and qualities. For most Arctic ecosystems, high gross N mineralization rates, N_2O, and CO_2 emissions were associated with moist soils containing large quantities of SOM and relatively labile C as determined using three techniques: 1) density fractionation of SOM and 2) solid-state CPMAS ^{13}C NMR, and 3) water-extractable organic matter. Most likely because of their high SOM mineralization (i.e., high N and C cycling), which promotes plant growth, Low and W landform units tended to accumulate high stocks of highly labile SOM compared to other landform units (i.e., Up and Back). These results greatly contribute to the understanding of how SOM properties may affect *in situ* soil N mineralization and GHG emissions Arctic terrestrial ecosystems. Assessing these relationships is particularly important to produce better models that evaluate SOM stocks and dynamics under several climate scenarios and across Arctic landscapes. Furthermore, this study contributes to our understanding of how SOM properties may influence plant production and local food supply for northern communities. Potential human-induced climatic changes affecting plant species, SOM biomass, and substrate characteristics can have consequences for C and N cycling in northern terrestrial ecosystems.

Chapter 6 : Synthesis and Overall Conclusions

6.1 Summary of Findings

This study characterized the properties of soil organic matter (SOM) in Arctic soils and their influence on soil nitrogen (N) and carbon (C) cycling processes at the landscape scale. Using a density fractionation technique, solid-state ^{13}C nuclear magnetic resonance (NMR) spectroscopy, and water-soluble organic C (WSOC) and N (WSON), this study showed that organic soils (>17% OC) contained about 13% more O-Alkyl-C (OAC) than mineral soils (<17% OC) (Chapter 3). Furthermore, organic soils had about 30% less Aromatic-C (AroC) than mineral soils, demonstrating that SOM in organic Arctic soils contained relatively more labile SOM compared to the SOM in mineral Arctic soils. On average, 53, 73, and 20% of the SOM was included in the light fraction (LF), whereas 24, 19, and 14% of the SOM was included in the heavy fraction (HF) at Churchill, Daring Lake, and Truelove, respectively. Furthermore, results show that Sub- and Low-Arctic organic soils sampled for this study store about 15% more OAC and 35% less AroC than High-Arctic organic soils, suggesting larger stocks of fresh and un-decomposed plant residues in Sub- and Low-Arctic compared to High-Arctic. Because combining high stocks of SOM and highly labile C with high climate change severity could trigger an enormous and rapid release of soil nutrients and greenhouse gases (GHGs), a better understanding of Arctic soil N and C cycling processes was required.

In order to estimate some of the *in situ* soil N and C cycling processes at the landscape scale (Chapter 4), two field-based techniques were used: ^{15}N dilution technique was used to estimate gross N mineralization and a chamber-based method coupled with Fourier transform infrared gas analyzer (FTiR) was used to assess GHG emissions (i.e., N_2O, CH_4, and CO_2). For all ecosystems, topography significantly influences soil N gross mineralization rates and GHG emissions, whereas topography had a slight impact on CH_4 emissions and significant impact on N_2O fluxes. Very small CH_4 and N_2O fluxes measured throughout ecosystems and landscapes may explain this small sensitivity to topography. At Churchill, gross N mineralization rates progressively increased from about 4 mg $N\text{-}NH_4^+$ kg^{-1} d^{-1} upper slopes to about 25 mg $N\text{-}NH_4^+$ kg^{-1} d^{-1} lower slopes. Accordantly, CO_2 emission rates at Daring Lake increased from about 0.5 µmol CO_2 m^{-2} s^{-1} upper slopes to about 2.3 µmol CO_2 m^{-2} s^{-1} lower slopes. Furthermore, results showed that N mineralization and CO_2 emissions rates vary across ecosystem, whereas no

difference in N_2O and CH_4 were found between ecosystems. These findings suggest that all factors influencing C and N cycling processes may not have similar effect across landscapes and ecosystems. Assessing the relationships between soil properties, SOM characteristics, and the measured soil N and C cycling processes was clearly the next step to a better understanding the soil N and C cycling rate differences across landscapes and ecosystems.

For most of the Arctic ecosystems, high gross N mineralization, N_2O, and CO_2 emissions were associated with relatively moist soils that store large quantities of SOM and relatively labile C, suggesting that moisture, SOM quantity, and labile SOM positively affect soil N and C cycling processes (Chapter 5). Furthermore, this study shows that Low and W landform units tended to accumulate more SOM and more labile SOM than Up and Back landform units. For all ecosystems, the measured parameters (25 variables) did not significantly explain CH_4 emission variations.

6.2 SOM Mineralization and C Budget: Climate Change and Landscape Perspectives

Most Arctic terrestrial ecosystems store large amounts of SOM. Furthermore, this study (Chapter 3) has clearly shown, based on knowledge of chemical structure, that Arctic soils store relatively more labile SOM compared to most temperate ecosystems. In addition, this study (Chapter 5) has demonstrated that both *in situ* soil gross N mineralization and soil GHG emissions (N_2O and CO_2) were positively affected by labile SOM and soil moisture. More severe climate change in this part of the globe highlights the vulnerability of Arctic soils compared to more temperate soil ecosystems. All climate change scenarios for terrestrial Arctic are currently predicting conditions that have the potential to enhance SOM mineralization and nutrient availability (e.g., warmer and wetter climate). A warmer climate, as well as higher soil nutrient availability will likely promote plant growth (e.g., shrubs and small trees) and hence, offset soil C and N losses through SOM mineralization in their biomass. Eventually, SOM mineralization (C and N) must decline as labile SOM is respired and a new steady state is reached. Therefore, the main question that still needs to be answered is: Will plant growth offset soil C and N losses throughout and across Arctic ecosystems? I believe that the responses of both soils and plants to climate change will

most likely be extremely variable throughout Arctic ecosystems and Arctic landscapes. The following reasons explain this position.

First, if the climate changes rapidly in some Arctic ecosystems, plants will not have time to establish and adapt to the change in growing conditions because plant adaptations may take decades to be achieved in such environments (Shaver et al., 1998). Therefore, if plants do not have time to establish, this "excess" of mineralized SOM will be lost via GHG emissions and water (e.g., leaching).

Second, if climate change involves more snow accumulation in some ecosystems – as expected by most climate models (Kattsov et al., 2005) – increasing snow depth will also increase soil winter temperatures and hence, soil winter microbial activities (Buckeridge et al., 2010a). During winter, large amounts of labile SOM can potentially be lost via GHG and water because Arctic soil microbes preferentially use labile SOM during winters (Grogan et al., 2001). Furthermore, recalcitrant C molecules are not available for decomposition at temperatures near the freezing point (Hobbie et al., 2000). Therefore, even if plants are already established, it is unlikely that plants will be able to utilize this entire 'excess' of soil nutrients mineralized during winters.

Third, it is possible that topography will limit plant biomass increase and expansion because of harsh (e.g., dry and windy) microclimates (Burke, 1989; Fahnestock et al., 2000). For example, topography poses a strong environmental barrier to species migration in Alaska, causing a pronounced time-lag in forest expansion, or even preventing expansion (Rupp et al., 2001). However, direct validation of this hypothesis is still extremely difficult because of the time-lag that vegetation takes to establish in such environments. Interestingly, this study shows that Low areas tended to store more labile C than Up areas, whereas Back areas tended to store relatively less, but more labile C than Low and Up areas, respectively (Chapter 5). More labile SOM was measured on landform units that experience more temperate and stable microclimate conditions such as Low and W because plants were able to grow and fully establish. Although Low and W areas tended to mineralize more C and N than Up and Back (Chapter 4), more fresh and undecomposed SOM associated with these landform units suggests that plants are currently off-setting C and N losses from SOM decomposition. Inversely, more recalcitrant SOM was measured on those landform units (e.g., Up and Back) that experience harsh microclimates

(Chapter 5) because plants were not able to grow and fully establish. Since this study (Chapter 4) demonstrated that all areas of the topography mineralized substantial amounts of C and N throughout Arctic ecosystems (i.e., had active C and N cycling processes), the recalcitrant SOM associated with Up and Back areas suggests that less fresh or 'new' SOM is produced and hence, plants are currently not off-setting C and N losses through SOM decomposition. Therefore, I believe that these less-vegetated landform units (e.g., Up and Back) are more at risk of losing net amounts C and N via GHG emissions than more vegetated landforms (e.g., Low and W). Furthermore, the results from this study strongly agree with the fact that SOM accumulation in Arctic mineral-dominated soils is mainly governed by the fresh plant inputs rather than low SOM mineralization rates.

6.3 Relevancy and Future Work

This work represents a major advance in the understanding of Arctic soil nutrient dynamics. Furthermore, this study greatly improved the knowledge and understanding of SOM characteristics and soil nutrient cycling of three distinct Arctic soil ecosystems. To my knowledge, this is the first study that simultaneously investigates the influence of SOM characteristics on soil N and C cycling processes at the landscape scale in such high-latitude ecosystems. Assessing these processes and their associated relationships will be particularly important to produce better models that evaluate soil C stocks and soil nutrient dynamics under several climate scenarios and across Arctic landscapes. Ultimately, better models can be made for helping scientists to better predict and explain the impacts of climate change on biological diversity that Arctic soils are supporting. Indirectly, this work will help Northerners to better adapt their local food habits and customs in a changing climate context. Adequately integrating studies from other disciplines (e.g., ecology, botany, zoology, climatology, and social sciences) to develop better tools for understanding the impact of climate change on both Arctic ecosystems and Northerners is definitely the next great challenge. The Arctic has entered into an unstable state; in many ways, the future of the Arctic is today.

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Chapter 8 : Appendices

Appendix A: Optimum Liquid Density in Separation of the Physically Uncomplexed Organic Matter in Arctic Soils.

SHORT COMMUNICATION

Optimum liquid density in separation of the physically uncomplexed organic matter in Arctic soils

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Paré, M. C. and Bedard-Haughn, A. 2011. **Optimum liquid density in separation of the physically uncomplexed organic matter in Arctic soils**. Can. J. Soil Sci. **91**: 65–68. Using an appropriate density to separate the soil light fraction (LF) and heavy fraction (HF) is an important aspect of the density fractionation technique. The effect of liquid density when separating the physically uncomplexed Arctic soil organic matter (SOM) was tested on three Arctic sites: High-Arctic, Low-Arctic, and Sub-Arctic. Our results showed that selecting the right density to use for Arctic soils is not unequivocal. Nevertheless, based on these two criteria: (1) the difference between the C:N values of the LF and HF needs to be as large as possible, and (2) the C:N value of the whole soil needs to be different from the C:N values of the LF and HF, the optimum density for all of our Arctic sites was between 1.49 and 1.55 g mL^{-1}. We concluded that 1.55g mL^{-1} was the conservative optimum liquid density to use to separate Arctic SOM light and heavy fractions.

Key words: Fractionation, carbon pools, labile, recalcitrant

Paré, M. C. et Bedard-Haughn, A. 2011. **Densité optimum du liquide pour la séparation de la matière organique non-complexée des sols de l'arctique**. Can. J. Soil Sci. **91**: 65–68. L'utilisation d'une densité appropriée de liquide est un aspect très important de la technique de séparation de la fraction légère et lourde de la matière organique. La variation de la densité du liquide a été testée pour la séparation de la matière organique non-complexée de trois écosystèmes arctiques : le haut arctique, le bas arctique et l'arctique de transition. Nos résultats ont démontré que la sélection optimale de la densité du liquide à utiliser pour les sols de l'arctique est hétérogène. Néanmoins, une densité acceptable entre 1.49 et 1.55 g mL^{-1} a pu être généralisée pour les trois écosystèmes de l'arctique selon les deux critères suivants: (1) les différences entre les ratios C:N des fractions légères et lourdes devraient être les plus grandes possibles et (2) les ratios C:N des fractions légères et lourdes devraient être différents des sols entiers. Finalement, nous suggérons 1.55 g mL^{-1} comme étant une valeur acceptable pour la séparation de la matière organique non-complexée des sols de l'arctique.

Mots clés: Fractionation, carbone, labile, récalcitrant

Cryosols, which are the dominant soil type in the Arctic, store a great amount of carbon (C) because soil organic matter (SOM) decomposition has historically been slower than plant growth (Weintraub and Schimel 2005). These permafrost-affected soils store approximately 25% of the world's organic C, which represents 61% of the C in all soils of North America (Tarnocai et al. 2008). It has been estimated that 63% of the C of permafrost-affected soils is included above the permafrost table (the active layer) (Ping et al. 2008). Furthermore, Arctic soil ecosystems store relatively labile SOM, hence the active layer soil and the SOM quality in these ecosystems play a major role related to soil greenhouse gas emissions, as well as nutrient cycling dynamics (Nadelhoffer et al. 1991; Hobbie et al. 2000; Wagner et al. 2005), highlighting the importance of studying Arctic SOM in a changing climate context.

The density fractionation technique of SOM has been widely used to separate fresh and decomposed SOM in almost all soil ecosystems, because both light (LF) and heavy fractions (HF) are physically and chemically distinct and are known to affect soil cycling processes (Cookson et al. 2005; Gregorich et al. 2006) such as soil CO_2 respiration (Janzen et al. 1992), N mineralization (Sollins et al. 1984; Hassink 1995; Curtin and Wen 1999), and N immobilization (Ladd et al. 1977; Ladd and Amato 1980). Therefore, fractions with a rapid turnover, such as LF versus HF, are generally assumed to play a dominant role in soil nutrient dynamics and cycling (Janzen et al. 1992) because LF contains more fresh and labile SOM (higher C:N values) than HF.

Using an appropriate density to separate the soil LF and HF is an important aspect of the density fractionation technique. Although density of 1.7 g mL^{-1} is commonly used to separate the LF from agricultural soils (Gregorich et al. 2006; Gregorich and Beare 2007), LF may constitute a major proportion of the SOM,

Abbreviations: **LF**, soil light fraction; **HF**, soil heavy fraction; **SOM**, soil organic matter

especially in cold and/or dry natural ecosystems such as the Arctic, where LF may constitute >70% of the whole SOM (Gundelwein et al. 2007). Therefore, finding an optimal liquid density is necessary to separate light and heavy fractions from Arctic soils.

The objectives of this study were: (1) to investigate the effect of liquid density when separating the physically uncomplexed Arctic SOM and (2) to evaluate the optimal liquid density to use for these soil ecosystems.

Sites and Sampling

The soils samples (0 10 cm) used for this study were collected from three distinct Arctic ecosystems: High-Arctic (Truelove Lowlands, NU; lat. 75°39′N, long. 84°37′W), Low-Arctic (Daring Lake, NWT; lat. 64°52′N, long. 111°34′W), and Sub-Arctic (Churchill, MB; lat. 58°45′N, long. 93°56′W) (Fig. 1). To capture the typical variability of each site, the sampling locations were evenly distributed along a soil moisture gradient from dry heath to wet sedge soil/plant ecosystems. Truelove Lowlands ($n=54$) and Daring Lake ($n=60$) were sampled in 2008 and Churchill ($n=138$) was sampled in 2009. Three composite samples (one for each site) were made by thoroughly mixing ~3 g of soil from each sampling location.

Organic Matter Density Fractionation

The SOM density pools fractionation technique was used to separate the uncomplexed LF and HF of SOM (Gregorich and Beare 2007). Approximately 20 mL of air-dried and 2 mm-sieved soil were shaken (200 rpm, 1 h) in 100 mL of sodium iodide (NaI) solution with a specific density adjusted to either 1.14, 1.21, 1.35, 1.49, 1.55, or 1.70 g mL^{-1}. After shaking, the samples were stored at ambient laboratory conditions for 48 h and covered to prevent density change in the NaI solution. Thereafter, the floating LF was collected using a vacuum system and filtered through a 0.45-μm membrane (Millipore Corporation, Billerica, MA). A second density fractionation cycle (as above) was done to ensure complete separation of the LF from the HF. Thereafter, both LF and HF fractions were (i) washed using 100 mL of 0.05 M $CaCl_2$ solution and 100 mL of di-ionized water, (ii) dried (60°C, 48 h), and (iii) ground (<420 μm) for analysis of organic C and total N using a carbon analyzer (model C632, Leco Corporation, St. Joseph, MI) and a CNS analyzer (model Leco-2000, Leco Corporation, St. Joseph, MI), respectively. To remove inorganic C, the whole soil and HF were acid-treated with 6% H_2SO_3 prior to analysis (Skjemstad and Baldock 2007). Three replicates for each liquid density were performed for each site.

Fig. 1. Sampling site locations throughout Canadian Arctic.

Discussion and Conclusions

Results showed that an increase in the liquid density increased the quantity of the LF and decreased the quantity of the HF (Fig. 2). Furthermore, an increase of the liquid density tended to progressively decrease C:N values of both LF and HF (Fig. 2) because both LF and HF were progressively enriched in N-rich and C-depleted compounds (more decomposed organic compounds), respectively (Wagai et al. 2009). The decrease in the C:N LF values with liquid density was also reported by Gregorich et al. (2006). However, in contrast to agricultural and forest soils, where the LF C:N values were fairly constant with densities at or below 1.8 g mL^{-1} and tending to decrease above 1.8 g mL^{-1} (Gregorich et al. 2006), our results suggest that LF C:N values decreased when liquid density was: >1.35 g mL^{-1} for Truelove (High-Arctic), never for Daring Lake (Low-Arctic), and >1.35 g mL^{-1} for Churchill (Sub-Arctic). Low LF quantity as well as high variability for LF might explain why no decrease in C:N value of the LF was measured for Daring Lake composite soil.

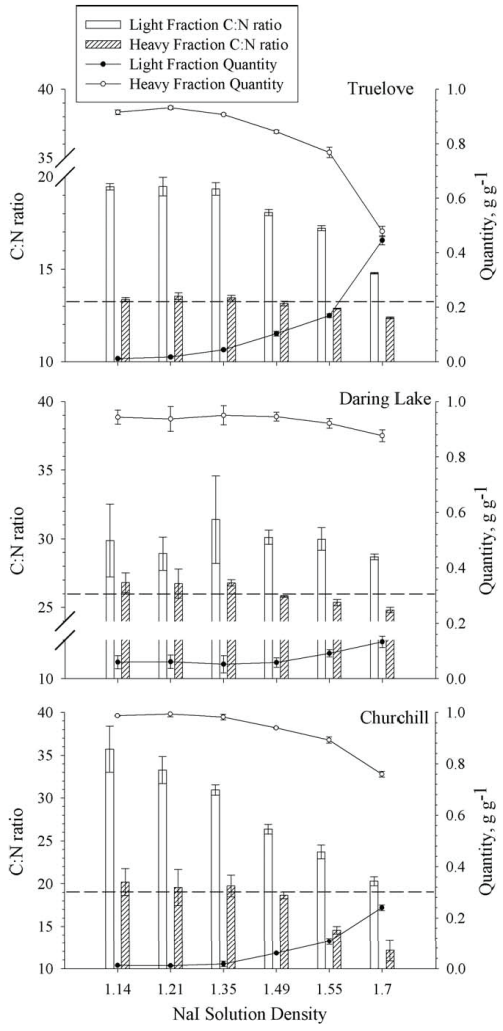

Fig. 2. The effect of liquid density on C:N ratio and quantity of the uncomplexed soil organic matter light (LF) and heavy (HF) fractions from Truelove, Daring Lake, and Churchill composite soil samples. Dashed lines represent the C:N values of the composite soil samples (whole soil). Error bars represent the standard deviation from the mean.

Our results suggest that the optimum density to use for density fractionation in Arctic soils is not uniform throughout the Arctic region. Selecting the right density to use for Arctic soils is not unequivocal and may also depend on the study objective, where carbon sequestration studies (more interested in HF) may choose heavier liquid than nutrient cycling studies (more interested in LF). Although our three Arctic sites had very different SOM materials (wide range of C:N values among sites), a density recommendation can be made based on the following criteria: (1) the difference between the C:N values of the LF and HF needs to be as large as possible and (2) the C:N value of the whole soil needs to be different from the C:N values of the LF and HF. The rationale is that LF and HF, as functional groups within the total organic matter pool, should each have a unique C:N ratio distinct from the whole soil, with the much higher C:N ratio of the LF indicating its less humified status. The use of C:N ratio allows for an optimum density to be identified independent of the total quantity of organic matter in the soil and is hence more applicable across ecosystems. Therefore, the optimum density for all of our Arctic sites was between 1.49 and 1.55 g mL^{-1} (Fig. 2). We suggest 1.55g mL^{-1} as the conservative optimum liquid density to separate Arctic SOM light and heavy fractions.

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Appendix B: Solid-state ^{13}C NMR Spectrum Examples

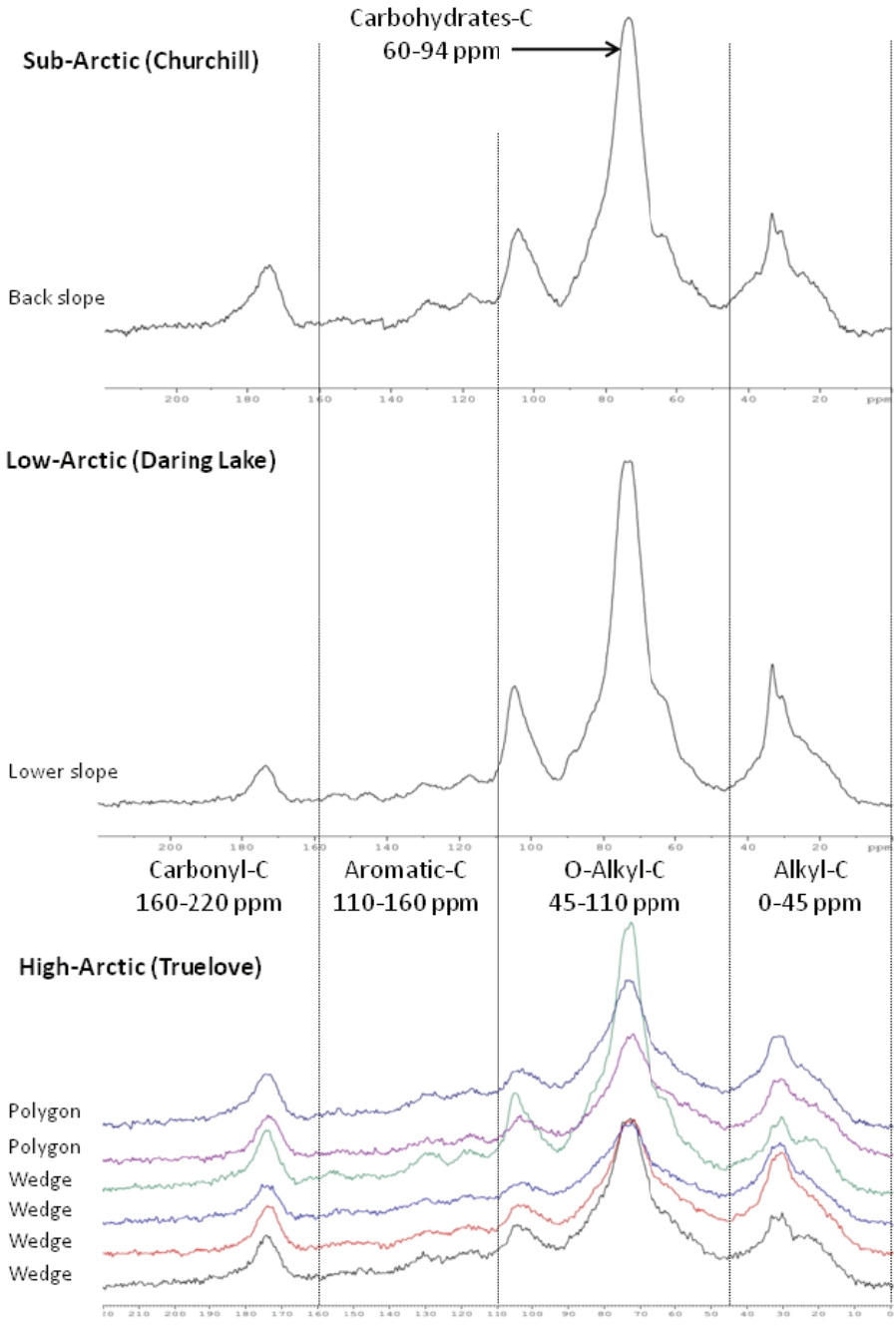

Figure B 1: An example of solid-state CPMAS ^{13}C NMR spectrums obtained.

Appendix C: Sites Sampled at Truelove

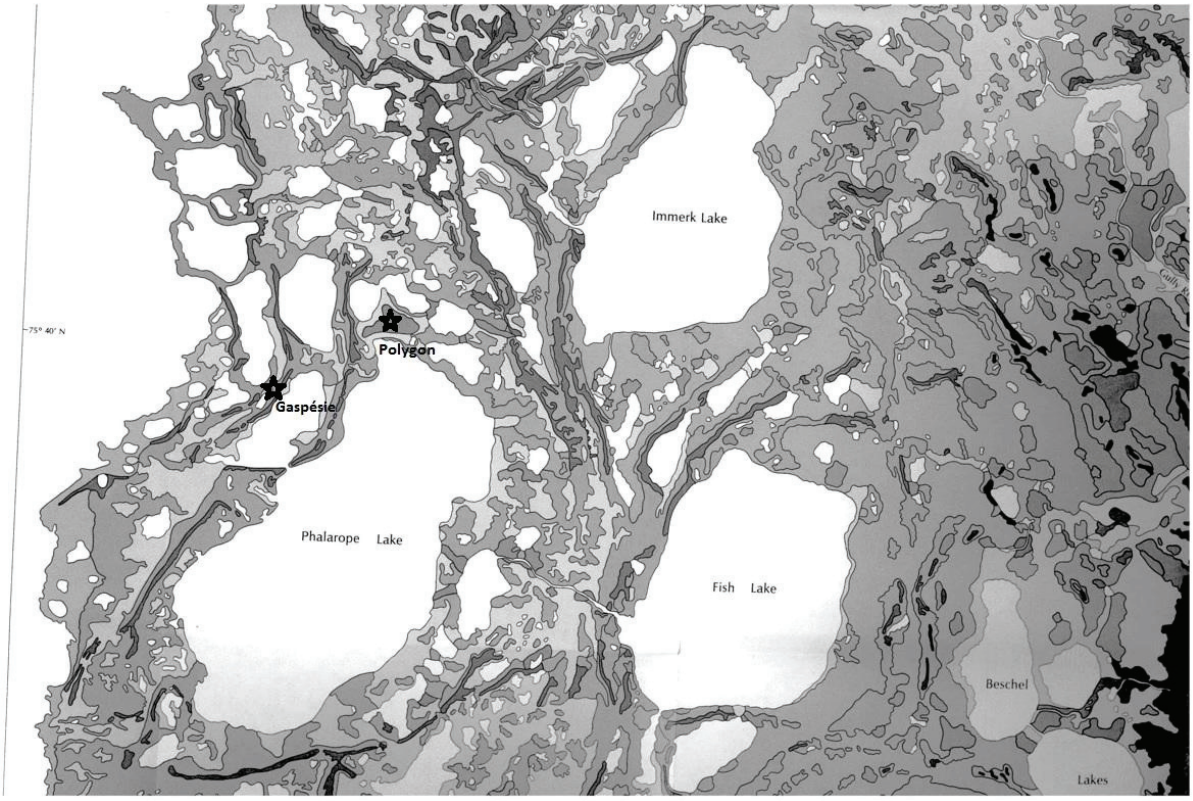

Figure C 1: Sites sampled (stars) at Truelove Lowlands. The map is adapted from Bliss (1977). ‘’Polygon’’ site is mapped as an ice-wedge polygon unit and ‘’Gaspésie’’ site is mapped as a raised beach unit.

Appendix D: Sampling Designs

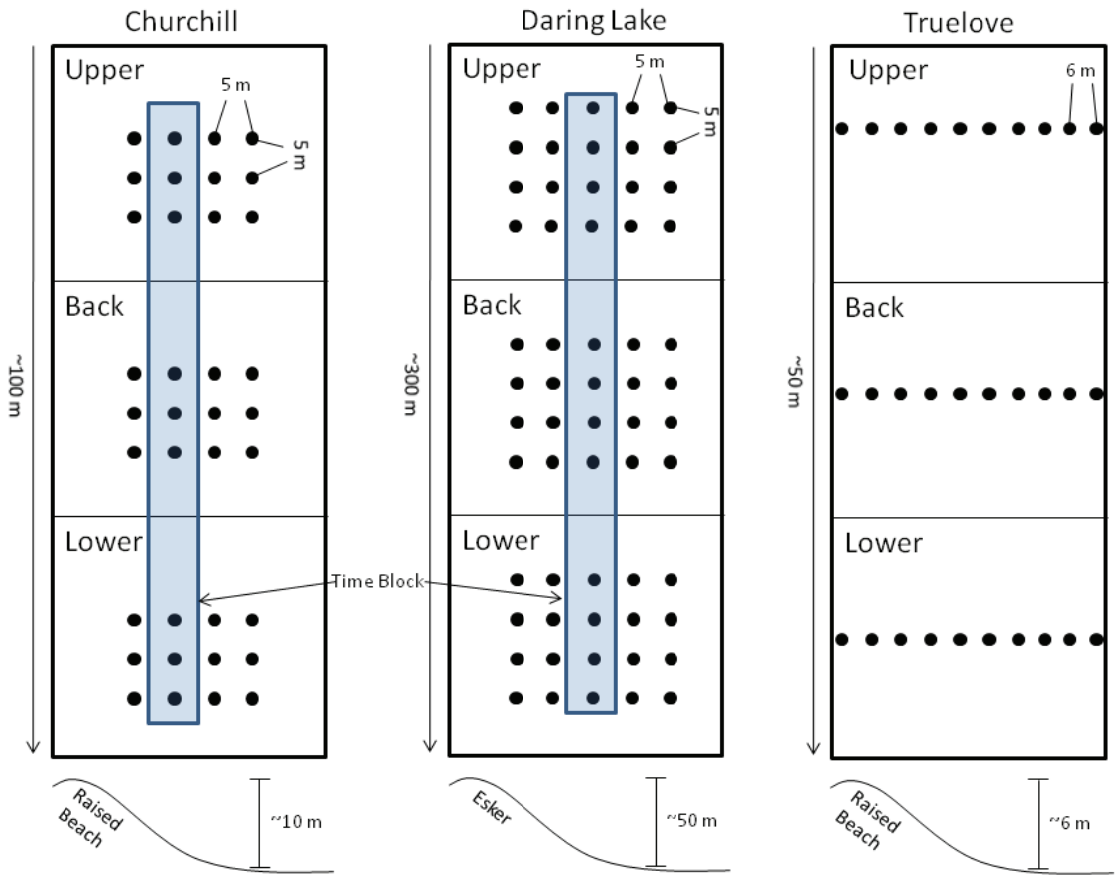

Figure D 1: Sampling designs used for this study.

Appendix E: Scatter Plots

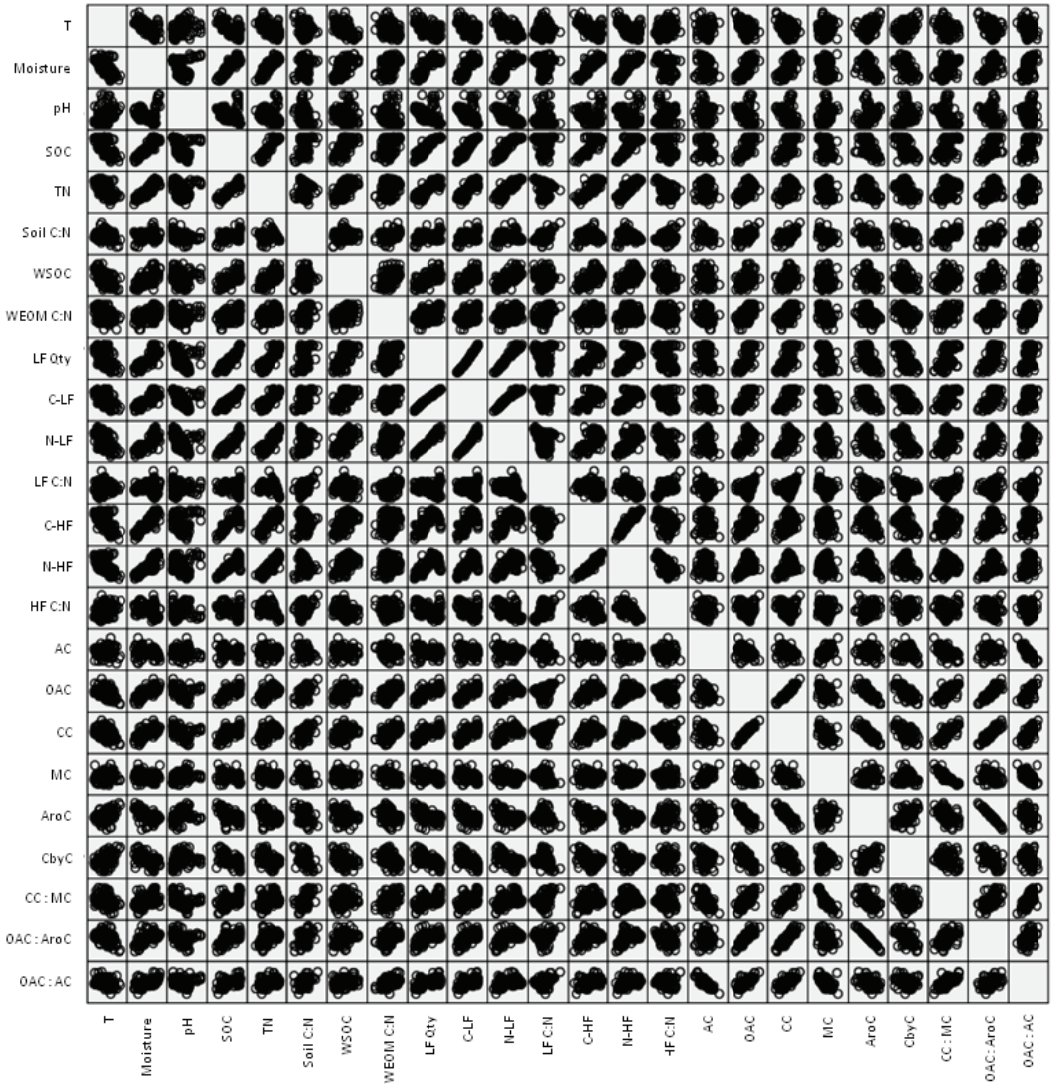

Figure E 1: Scatterplots showing linear relationships among the data from Churchill.

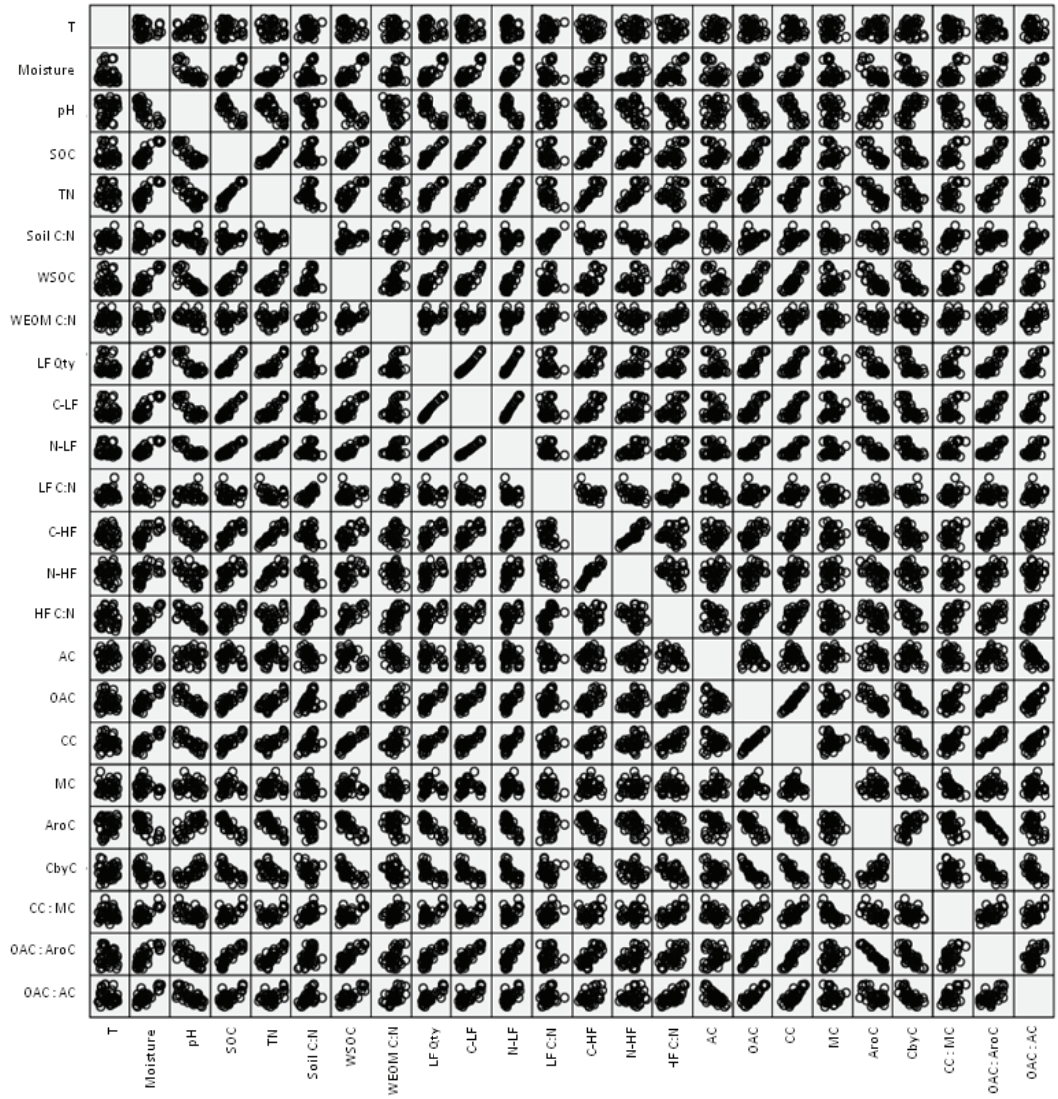

Figure E 2: Scatterplots showing linear relationships among the data from Daring Lake.

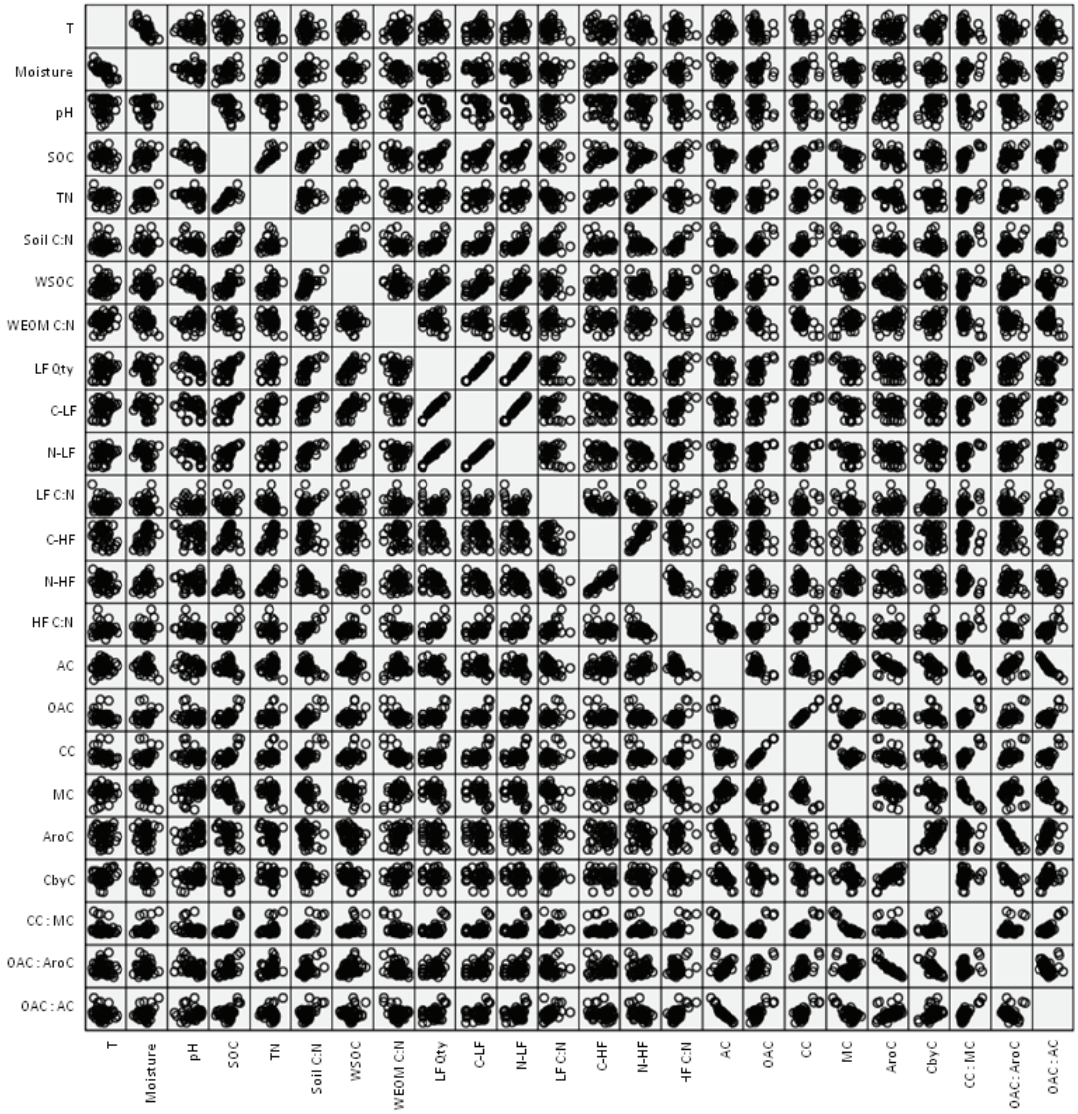

Figure E 3: Scatterplots showing linear relationships among the data from Truelove.

Appendix F: Raw Data

Table F 1: N and C cycling processes.

Ecosystem	Point	Topo	N Min.	CO_2	CH_4	N_2O
			mg $kg^{-1}d^{-1}$	umol $m^{-2}s^{-1}$	nmol $m^{-2}s^{-1}$	nmol $m^{-2}s^{-1}$
Churchill	DU1	Upper	0.82	0.11	0.49	-1.13
Churchill	DU2	Upper	4.15			
Churchill	DU3	Upper	6.49			
Churchill	DU4	Upper	5.10	0.07	0.40	0.27
Churchill	DU5	Upper	4.71	0.15	-0.24	-0.21
Churchill	DU6	Upper	8.79	0.28	-0.33	0.31
Churchill	DU7	Upper	7.06			
Churchill	DU8	Upper	5.05	0.09	0.00	0.15
Churchill	DU9	Upper	8.64	0.14	-0.96	-1.82
Churchill	DU10	Upper	5.15	0.06	0.35	-0.16
Churchill	DU11	Upper	3.50	0.04	-0.41	0.30
Churchill	DU12	Upper	12.57	0.16	0.40	0.06
Churchill	DB1	Back	3.37	0.07	-0.77	0.03
Churchill	DB2	Back	13.56			
Churchill	DB3	Back	50.39	0.56	0.12	0.04
Churchill	DB4	Back	7.06	0.33	0.51	0.70
Churchill	DB5	Back	5.89	0.27	-0.33	-0.60
Churchill	DB6	Back	14.41	0.32	1.18	-0.31
Churchill	DB7	Back	10.71			
Churchill	DB8	Back	10.96	0.14	-1.17	-0.19
Churchill	DB9	Back	19.01	0.35	0.87	0.50
Churchill	DB10	Back	7.40			
Churchill	DB11	Back	3.32			
Churchill	DB12	Back	27.51	0.30	0.44	0.02
Churchill	DL1	Lower	9.17	0.42	-0.27	0.51
Churchill	DL2	Lower	19.65			
Churchill	DL3	Lower	10.99	0.09	-0.09	0.13
Churchill	DL4	Lower	43.03	0.61	-0.51	0.10
Churchill	DL5	Lower	20.72	0.31	-0.27	-0.13
Churchill	DL6	Lower	30.71			
Churchill	DL7	Lower	22.52	0.30	0.52	-0.42
Churchill	DL8	Lower	15.23	0.47	0.43	0.15
Churchill	DL9	Lower	32.57			
Churchill	DL10	Lower	25.40	0.35	-0.54	-0.49
Churchill	DL11	Lower	10.80	0.82	0.11	0.43
Churchill	DL12	Lower	29.28	0.30	0.52	0.00
Churchill	BgU1	Upper	5.93	0.30	-1.83	0.88
Churchill	BgU2	Upper	6.97	-0.14	0.02	0.07
Churchill	BgU3	Upper	3.85	0.37	-1.78	-0.50
Churchill	BgU4	Upper	4.10	0.59	-1.94	-0.03
Churchill	BgU5	Upper	5.96	0.28	-0.03	-0.04
Churchill	BgU6	Upper	3.13	0.38	-0.47	-0.20
Churchill	BgU7	Upper	4.38	0.64	0.01	0.41

Ecosystem	Point	Topo	N Min.	CO_2	CH_4	N_2O
			mg $kg^{-1}d^{-1}$	umol $m^{-2}s^{-1}$	nmol $m^{-2}s^{-1}$	nmol $m^{-2}s^{-1}$
Churchill	BgU8	Upper	2.72	0.32	-2.16	-0.07
Churchill	BgU9	Upper	2.26	0.46	-1.65	-0.73
Churchill	BgU10	Upper	4.35	0.67	0.27	-0.37
Churchill	BgU11	Upper	4.67	0.75	-1.11	-0.97
Churchill	BgU12	Upper	2.09	1.03	-0.11	-1.19
Churchill	BgB1	Back	6.47			
Churchill	BgB2	Back	5.91			
Churchill	BgB3	Back	8.98			
Churchill	BgB4	Back	9.87	0.25	-0.88	0.43
Churchill	BgB5	Back	5.25	0.56	0.05	-0.34
Churchill	BgB6	Back	41.45	0.36	0.48	0.49
Churchill	BgB7	Back	75.72	0.69	0.32	0.22
Churchill	BgB8	Back	25.29	0.99	1.24	-0.42
Churchill	BgB9	Back	15.39			
Churchill	BgB10	Back	4.88	0.40	0.01	0.70
Churchill	BgB11	Back	0.63	0.47	0.13	-0.94
Churchill	BgB12	Back	5.46			
Churchill	BgL1	Lower	79.09	0.86	-0.25	0.11
Churchill	BgL2	Lower	-0.84			
Churchill	BgL3	Lower	33.82	0.39	0.29	-0.17
Churchill	BgL4	Lower	17.69	1.15	0.66	-0.13
Churchill	BgL5	Lower	27.22			
Churchill	BgL6	Lower	19.87	0.65	0.62	0.51
Churchill	BgL7	Lower	14.08	0.52	0.36	-0.97
Churchill	BgL8	Lower	13.10	1.29	0.54	-0.70
Churchill	BgL9	Lower	26.13	0.69	-0.16	0.60
Churchill	BgL10	Lower	26.24	1.04	-1.19	0.25
Churchill	BgL11	Lower	6.83			
Churchill	BgL12	Lower	41.94	1.02	0.62	0.91
Churchill	BrU1	Upper	3.01	-0.03	-2.17	0.34
Churchill	BrU2	Upper	3.57	0.16	0.31	-0.12
Churchill	BrU3	Upper	5.99	0.19	1.55	-1.12
Churchill	BrU4	Upper	3.56			
Churchill	BrU5	Upper	2.80	0.32	-0.40	0.45
Churchill	BrU6	Upper	2.23	0.29	0.04	0.21
Churchill	BrU7	Upper	2.42	0.31	-1.46	-0.45
Churchill	BrU8	Upper	3.22	0.14	0.30	-0.20
Churchill	BrU9	Upper	4.57	0.27	-0.16	0.54
Churchill	BrU10	Upper	2.13			
Churchill	BrU11	Upper	2.72	0.36		0.12
Churchill	BrU12	Upper	2.76	0.35	4.58	-0.42
Churchill	BrB1	Back	4.51	0.13	-0.48	0.31
Churchill	BrB2	Back	8.79	0.27	-0.32	-0.11
Churchill	BrB3	Back	3.84	0.58	1.13	0.23
Churchill	BrB4	Back	3.41	0.49	0.00	0.51

Ecosystem	Point	Topo	N Min.	CO_2	CH_4	N_2O
			mg $kg^{-1}d^{-1}$	umol $m^{-2}s^{-1}$	nmol $m^{-2}s^{-1}$	nmol $m^{-2}s^{-1}$
Churchill	BrB5	Back	5.64	0.71	-0.57	-0.39
Churchill	BrB6	Back	3.91			
Churchill	BrB7	Back	2.33	0.42	-0.42	0.17
Churchill	BrB8	Back	4.99	0.92	0.36	-0.21
Churchill	BrB9	Back	2.81	0.52	1.53	-0.04
Churchill	BrB10	Back	2.92	0.47	-0.11	-0.25
Churchill	BrB11	Back	3.74	0.64	-0.42	-0.17
Churchill	BrB12	Back	4.95	0.84	-0.18	0.28
Churchill	BrL1	Lower	63.53	0.35	0.41	-0.08
Churchill	BrL2	Lower	36.63	0.48	0.61	0.02
Churchill	BrL3	Lower	107.61	0.22	0.74	-0.43
Churchill	BrL4	Lower	11.58	0.25	0.50	-0.26
Churchill	BrL5	Lower	7.02			
Churchill	BrL6	Lower	2.43	0.17	2.31	-0.21
Churchill	BrL7	Lower	10.26	0.53	2.66	0.28
Churchill	BrL8	Lower	17.22	0.84	1.35	0.37
Churchill	BrL9	Lower	3.15	0.55	3.46	-0.19
Churchill	BrL10	Lower	20.33	0.81	0.50	0.47
Churchill	BrL11	Lower	17.02	1.04	1.40	0.42
Churchill	BrL12	Lower	14.57	0.29	0.56	-0.07
Churchill	HW1	Wedge	15.91	0.61	-0.07	0.33
Churchill	HW2	Wedge	13.77	0.62	-0.50	0.11
Churchill	HW3	Wedge	18.97	0.57	-0.46	0.02
Churchill	HW4	Wedge	4.00	0.50	0.43	0.14
Churchill	HW5	Wedge	14.51	0.65	-0.50	
Churchill	HW6	Wedge	22.36	0.42	-0.31	0.19
Churchill	HW7	Wedge	28.01	1.08	0.00	-0.50
Churchill	HW8	Wedge	11.35	0.75	0.04	0.10
Churchill	HW9	Wedge	10.90	0.57	-0.93	-0.17
Churchill	HW10	Wedge	12.74	0.94		-0.08
Churchill	HW11	Wedge	12.63	0.70	-1.01	0.50
Churchill	HW12	Wedge	14.31	1.15	-0.13	0.00
Churchill	HW13	Wedge	10.60	0.56	0.10	0.07
Churchill	HW14	Wedge	16.21	0.35	0.04	0.02
Churchill	HW15	Wedge	21.88	0.66	0.71	0.30
Churchill	HP1	Hummock	-0.50	0.88	0.14	0.34
Churchill	HP2	Hummock	5.04	0.27	-0.31	0.27
Churchill	HP3	Hummock	2.78	0.49	0.71	-0.42
Churchill	HP4	Hummock	4.25			
Churchill	HP5	Hummock	12.77	0.11	-0.46	0.03
Churchill	HP6	Hummock	1.98	0.16	0.08	-0.32
Churchill	HP7	Hummock	10.92	0.11	0.04	0.36
Churchill	HP8	Hummock	2.59			
Churchill	HP9	Hummock	2.99	0.45	-0.54	-0.34
Churchill	HP10	Hummock	4.82	0.59	0.03	0.02

Ecosystem	Point	Topo	N Min.	CO_2	CH_4	N_2O
			mg $kg^{-1}d^{-1}$	umol $m^{-2}s^{-1}$	nmol $m^{-2}s^{-1}$	nmol $m^{-2}s^{-1}$
Churchill	HP11	Hummock	12.10			
Churchill	HP12	Hummock	7.20	0.37	0.17	-0.04
Churchill	HP13	Hummock	1.06	0.11	1.52	0.15
Churchill	HP14	Hummock	7.56	0.15	0.21	0.15
Churchill	HP15	Hummock	9.94	0.22	0.39	-0.23
Daring Lake	Ua15	Up	0.34	0.24	0.56	-10.53
Daring Lake	Ua10	Up	1.50	1.55	-1.43	-0.16
Daring Lake	Ua5	Up	1.01	0.60	13.86	-0.41
Daring Lake	Ua0	Up	-0.36	-0.09	-0.64	-4.19
Daring Lake	Ba15	Back	0.27	4.59	-6.00	-0.34
Daring Lake	Ba10	Back	0.15	1.56	-9.77	-0.13
Daring Lake	Ba5	Back	0.51	2.30	7.26	0.11
Daring Lake	Ba0	Back	0.10	3.08	9.38	3.44
Daring Lake	La15	Low	-0.08	3.05	3.38	-0.77
Daring Lake	La10	Low	-0.05	5.99	5.64	2.63
Daring Lake	La5	Low	0.15	5.33	-5.78	-2.16
Daring Lake	La0	Low	0.94	3.56	0.58	-2.03
Daring Lake	Ub15	Up	0.58	1.10	-5.00	0.64
Daring Lake	Ub10	Up	0.64	0.24	0.85	2.38
Daring Lake	Ub5	Up	0.91	0.17	1.43	2.41
Daring Lake	Ub0	Up	0.63	0.23	0.15	4.44
Daring Lake	Bb15	Back	0.09	1.66	-12.71	-0.50
Daring Lake	Bb10	Back	0.72	1.44	-7.13	1.10
Daring Lake	Bb5	Back	0.02	1.01	4.62	-1.25
Daring Lake	Bb0	Back	0.20	0.36	6.63	-0.13
Daring Lake	Lb15	Low	-0.02	1.04	1.28	-1.67
Daring Lake	Lb10	Low	0.41	1.05	12.88	-0.20
Daring Lake	Lb5	Low	0.13	1.29	3.45	1.73
Daring Lake	Lb0	Low	0.54	0.20	1.47	6.87
Daring Lake	Uc15	Up	0.98	0.28	1.51	5.89
Daring Lake	Uc10	Up	0.42	0.29	2.33	6.52
Daring Lake	Uc5	Up	0.93	1.05	-5.01	-1.10
Daring Lake	Uc0	Up	0.77	0.49	-0.31	-1.69
Daring Lake	Bc15	Back	1.31	1.48	-2.64	0.76
Daring Lake	Bc10	Back	1.49	3.58	2.52	5.32
Daring Lake	Bc5	Back	1.44	4.79	10.06	2.43
Daring Lake	Bc0	Back	0.07	0.26	0.92	-1.84
Daring Lake	Lc15	Low	0.62	3.17	5.54	1.55
Daring Lake	Lc10	Low	0.01	2.29	-6.35	-1.16
Daring Lake	Lc5	Low	0.52	2.27	-2.07	2.28
Daring Lake	Lc0	Low	1.83	6.80	4.50	4.96
Daring Lake	Ud15	Up	0.74	0.26	-1.80	4.96
Daring Lake	Ud10	Up	0.84	0.21	1.11	3.75
Daring Lake	Ud5	Up	0.43	-0.22	0.12	0.33
Daring Lake	Ud0	Up	0.51	0.01	2.15	-0.93

Ecosystem	Point	Topo	N Min.	CO_2	CH_4	N_2O
			mg $kg^{-1}d^{-1}$	umol $m^{-2}s^{-1}$	nmol $m^{-2}s^{-1}$	nmol $m^{-2}s^{-1}$
Daring Lake	Bd15	Back	0.06	1.00	-9.73	-3.62
Daring Lake	Bd10	Back	1.21	2.72	-13.23	-2.56
Daring Lake	Bd5	Back	0.61	1.02	-4.48	3.21
Daring Lake	Bd0	Back	0.01	1.04	-6.62	-5.29
Daring Lake	Ld15	Low	-0.03	2.33	7.17	0.97
Daring Lake	Ld10	Low	18.58	1.57	-5.14	1.58
Daring Lake	Ld5	Low	1.03	0.80	9.86	-0.83
Daring Lake	Ld0	Low	2.22	0.77	-4.71	1.55
Daring Lake	Ue15	Up	0.01	1.54	14.54	-2.48
Daring Lake	Ue10	Up	0.70	0.71	1.71	-8.87
Daring Lake	Ue5	Up	0.77	0.49	5.75	0.66
Daring Lake	Ue0	Up	-0.05	0.05	0.69	3.91
Daring Lake	Be15	Back	0.57	0.86	0.88	-0.70
Daring Lake	Be10	Back	0.83	2.83	4.81	-2.57
Daring Lake	Be5	Back	0.67	3.47	-3.18	0.69
Daring Lake	Be0	Back	0.10	2.01	-7.97	-2.75
Daring Lake	Le15	Low	-0.05	1.69	-2.01	-1.37
Daring Lake	Le10	Low	0.15	0.53	1.69	-0.78
Daring Lake	Le5	Low	-0.92	0.37	0.39	-5.57
Daring Lake	Le0	Low	0.34	1.50	0.05	1.17
Truelove	TU1	Up	5.44			
Truelove	TU2	Up	3.64			
Truelove	TU3	Up	3.11			
Truelove	TU4	Up	5.01			
Truelove	TU5	Up	5.51			
Truelove	TU6	Up	4.86			
Truelove	TU7	Up	5.90			
Truelove	TU8	Up	3.64			
Truelove	TU9	Up	5.04			
Truelove	TU10	Up	3.22			
Truelove	TB1	Back	5.24			
Truelove	TB2	Back	5.86			
Truelove	TB3	Back	5.14			
Truelove	TB4	Back	6.97			
Truelove	TB5	Back	3.14			
Truelove	TB6	Back	8.38			
Truelove	TB7	Back	4.20			
Truelove	TB8	Back	3.98			
Truelove	TB9	Back	3.88			
Truelove	TB10	Back	4.07			
Truelove	TL1	Low	3.12			
Truelove	TL2	Low	4.37			
Truelove	TL3	Low	6.21			
Truelove	TL4	Low	0.06			
Truelove	TL5	Low	3.07			

Ecosystem	Point	Topo	N Min.	CO_2	CH_4	N_2O
			mg $kg^{-1}d^{-1}$	umol $m^{-2}s^{-1}$	nmol $m^{-2}s^{-1}$	nmol $m^{-2}s^{-1}$
Truelove	TL6	Low	1.02			
Truelove	TL7	Low	20.99			
Truelove	TL8	Low	8.84			
Truelove	TL9	Low	20.14			
Truelove	TL10	Low	32.46			
Truelove	W1.1	Wedge	1.79			
Truelove	W1.2	Wedge	8.72			
Truelove	W2.1	Wedge	4.10			
Truelove	W2.2	Wedge	5.10			
Truelove	W3	Wedge	1.92			
Truelove	W4	Wedge	15.27			
Truelove	W5	Wedge	3.39			
Truelove	W6	Wedge	6.51			
Truelove	W7	Wedge	3.86			
Truelove	W8	Wedge	0.92			
Truelove	W9	Wedge	3.62			
Truelove	W10	Wedge	10.17			
Truelove	P1.1	Hummock	4.09			
Truelove	P1.2	Hummock	5.22			
Truelove	P2.1	Hummock	2.85			
Truelove	P2.2	Hummock	3.47			
Truelove	P3	Hummock	0.63			
Truelove	P4	Hummock	2.32			
Truelove	P5	Hummock	4.75			
Truelove	P6	Hummock	8.28			
Truelove	P7	Hummock	2.91			
Truelove	P8	Hummock	2.62			
Truelove	P9	Hummock	1.73			
Truelove	P10	Hummock	7.60			

Table F 2: Soil general properties.

Ecosystem	Point	Topo	T	Moisture	pH	SOC	TN	Soil C:N
			°C	g H_2O g^{-1}		g $100g^{-1}$	g $100g^{-1}$	
Churchill	DU1	Upper	7.10	0.15	6.76	4.53	0.27	16.70
Churchill	DU2	Upper	7.60	0.17	6.78	5.44	0.36	14.92
Churchill	DU3	Upper	7.20	0.27	6.67	8.87	0.38	23.24
Churchill	DU4	Upper	8.60	0.18	6.70	9.14	0.50	18.35
Churchill	DU5	Upper	9.90	0.14	6.72	6.65	0.36	18.33
Churchill	DU6	Upper	8.30	0.20	6.65	5.54	0.38	14.47
Churchill	DU7	Upper	9.30	0.20	6.83	5.27	0.33	16.03
Churchill	DU8	Upper	8.90	0.19	6.84	5.26	0.36	14.80
Churchill	DU9	Upper	9.10	0.22	6.83	6.31	0.50	12.64
Churchill	DU10	Upper	10.20	0.22	6.77	7.09	0.54	13.05
Churchill	DU11	Upper	11.70	0.15	6.87	6.62	0.37	17.85
Churchill	DU12	Upper	10.50	0.28	6.74	12.10	0.59	20.64
Churchill	DB1	Back	5.40	0.35	6.60	11.61	0.51	22.96
Churchill	DB2	Back	4.50	1.88	6.31	44.07	1.51	29.24
Churchill	DB3	Back	4.50	1.61	6.35	45.08	1.93	23.35
Churchill	DB4	Back	4.90	0.58	6.24	27.97	1.02	27.34
Churchill	DB5	Back	4.80	1.18	6.38	29.40	1.50	19.56
Churchill	DB6	Back	5.40	2.48	6.44	38.71	2.33	16.59
Churchill	DB7	Back	5.40	0.77	6.10	21.53	1.32	16.37
Churchill	DB8	Back	5.80	1.16	6.46	34.59	1.70	20.35
Churchill	DB9	Back	6.30	2.14	6.26	38.51	2.49	15.47
Churchill	DB10	Back	6.00	0.49	6.46	12.60	0.46	27.53
Churchill	DB11	Back	4.40	1.90	6.23	42.74	1.99	21.52
Churchill	DB12	Back	5.40	1.85	6.04	41.74	2.28	18.32
Churchill	DL1	Lower	3.60	2.28	5.77	44.09	2.40	18.36
Churchill	DL2	Lower	3.70	1.61	5.48	45.92	1.59	28.90
Churchill	DL3	Lower	2.90	2.71	5.52	44.66	2.50	17.86
Churchill	DL4	Lower	4.50	1.56	5.39	45.91	1.69	27.25
Churchill	DL5	Lower	3.70	2.85	5.36	45.42	2.78	16.31
Churchill	DL6	Lower	2.70	2.68	6.05	43.67	2.48	17.63
Churchill	DL7	Lower	4.60	3.34	5.17	45.55	2.82	16.13
Churchill	DL8	Lower	4.30	2.53	5.09	46.02	2.57	17.94
Churchill	DL9	Lower	4.10	2.90	5.17	45.85	2.77	16.56
Churchill	DL10	Lower	4.30	3.34	4.84	46.37	3.32	13.95
Churchill	DL11	Lower	4.00	2.03	5.40	44.39	1.84	24.13
Churchill	DL12	Lower	3.40	2.49	5.35	44.01	2.35	18.75
Churchill	BgU1	Upper	9.50	0.25	6.79	6.58	0.47	13.98
Churchill	BgU2	Upper	9.00	0.27	6.75	7.44	0.47	15.84
Churchill	BgU3	Upper	10.10	0.05	6.82	1.79	0.20	8.81
Churchill	BgU4	Upper	10.10	0.09	6.78	2.44	0.22	11.09
Churchill	BgU5	Upper	11.70	0.26	6.60	8.36	0.63	13.19
Churchill	BgU6	Upper	10.40	0.26	6.63	5.72	0.47	12.10
Churchill	BgU7	Upper	11.40	0.12	6.82	3.08	0.24	13.06

Ecosystem	Point	Topo	T	Moisture	pH	SOC	TN	Soil C:N
			°C	g H_2O g^{-1}		g $100g^{-1}$	g $100g^{-1}$	
Churchill	BgU8	Upper	13.80	0.05	6.78	1.97	0.26	7.68
Churchill	BgU9	Upper	12.70	0.09	6.69	2.97	0.41	7.20
Churchill	BgU10	Upper	14.60	0.11	6.86	4.01	0.28	14.26
Churchill	BgU11	Upper	12.70	0.11	6.73	3.60	0.28	12.96
Churchill	BgU12	Upper	17.50	0.03	6.85	0.78	0.11	6.95
Churchill	BgB1	Back	6.60	0.81	6.18	10.47	0.51	20.71
Churchill	BgB2	Back	6.10	0.60	6.08	10.58	0.52	20.39
Churchill	BgB3	Back	4.30	1.69	6.36	14.83	0.75	19.66
Churchill	BgB4	Back	5.00	2.04	5.77	27.88	1.25	22.39
Churchill	BgB5	Back	4.90	0.78	6.21	10.51	0.38	27.92
Churchill	BgB6	Back	4.40	2.83	6.80	41.11	1.94	21.22
Churchill	BgB7	Back	4.70	3.27	6.49	42.29	1.48	28.54
Churchill	BgB8	Back	4.60	2.88	6.87	35.23	1.65	21.30
Churchill	BgB9	Back	6.20	2.46	6.68	28.52	1.41	20.23
Churchill	BgB10	Back	8.00	1.60	6.56	16.17	0.91	17.82
Churchill	BgB11	Back	7.00	1.16	6.03	16.81	0.94	17.90
Churchill	BgB12	Back	5.10	1.47	6.33	14.71	0.78	18.82
Churchill	BgL1	Lower	3.10	7.75	6.87	30.25	1.30	23.22
Churchill	BgL2	Lower	6.00	5.59	6.93	40.40	2.23	18.13
Churchill	BgL3	Lower	8.10	4.42	7.02	39.53	2.54	15.56
Churchill	BgL4	Lower	9.00	5.74	7.08	38.54	2.30	16.76
Churchill	BgL5	Lower	7.30	5.65	7.09	30.15	1.76	17.13
Churchill	BgL6	Lower	9.70	5.84	7.08	34.31	2.12	16.18
Churchill	BgL7	Lower	9.00	5.27	7.03	38.13	2.72	14.02
Churchill	BgL8	Lower	6.30	4.74	7.03	40.49	2.35	17.23
Churchill	BgL9	Lower	5.50	3.50	6.92	41.82	1.97	21.23
Churchill	BgL10	Lower	11.40	4.84	6.89	39.65	2.81	14.11
Churchill	BgL11	Lower	10.80	5.49	6.97	38.80	2.48	15.65
Churchill	BgL12	Lower	5.90	7.46	7.09	41.15	1.47	27.99
Churchill	BrU1	Upper	9.90	0.04	6.75	2.73	0.09	29.79
Churchill	BrU2	Upper	9.30	0.07	6.51	3.98	0.15	27.06
Churchill	BrU3	Upper	9.50	0.11	6.50	4.79	0.18	26.75
Churchill	BrU4	Upper	10.70	0.08	6.72	4.49	0.17	26.26
Churchill	BrU5	Upper	10.10	0.05	6.61	3.63	0.15	24.22
Churchill	BrU6	Upper	10.60	0.08	6.47	4.19	0.16	25.86
Churchill	BrU7	Upper	10.00	0.06	6.64	3.88	0.17	22.28
Churchill	BrU8	Upper	10.80	0.06	6.60	4.56	0.17	27.28
Churchill	BrU9	Upper	9.70	0.11	6.49	6.61	0.24	27.21
Churchill	BrU10	Upper	11.70	0.08	6.46	4.74	0.20	23.45
Churchill	BrU11	Upper	11.50	0.14	6.46	7.71	0.26	29.30
Churchill	BrU12	Upper	9.60	0.12	6.34	5.89	0.23	25.60
Churchill	BrB1	Back	7.10	0.16	6.29	5.21	0.19	26.87
Churchill	BrB2	Back	7.00	0.26	6.27	6.92	0.27	25.36
Churchill	BrB3	Back	7.40	0.53	6.24	8.12	0.27	30.17
Churchill	BrB4	Back	8.70	0.12	6.22	6.55	0.26	24.82

Ecosystem	Point	Topo	T	Moisture	pH	SOC	TN	Soil C:N
			°C	g H_2O g^{-1}		g $100g^{-1}$	g $100g^{-1}$	
Churchill	BrB5	Back	8.30	0.20	6.25	8.02	0.27	29.91
Churchill	BrB6	Back	8.00	0.52	6.12	6.73	0.26	25.50
Churchill	BrB7	Back	9.30	0.07	6.48	3.23	0.17	18.88
Churchill	BrB8	Back	9.50	0.26	6.41	5.45	0.24	23.11
Churchill	BrB9	Back	9.90	0.45	6.44	7.06	0.26	26.93
Churchill	BrB10	Back	9.30	0.12	6.52	4.69	0.22	21.73
Churchill	BrB11	Back	10.60	0.36	6.36	5.63	0.28	19.89
Churchill	BrB12	Back	10.30	0.58	6.60	7.96	0.30	26.43
Churchill	BrL1	Lower	5.20	2.90	6.59	31.62	1.31	24.14
Churchill	BrL2	Lower	4.50	2.67	6.63	20.55	1.00	20.59
Churchill	BrL3	Lower	6.40	2.72	6.65	29.54	1.49	19.83
Churchill	BrL4	Lower	5.60	1.54	6.52	26.90	0.47	57.23
Churchill	BrL5	Lower	5.90	2.63	6.30	11.26	1.05	10.72
Churchill	BrL6	Lower	6.50	1.66	6.27	16.07	0.58	27.52
Churchill	BrL7	Lower	5.70	1.70	6.29	10.70	0.51	21.10
Churchill	BrL8	Lower	6.40	1.73	6.07	12.62	0.83	15.15
Churchill	BrL9	Lower	6.70	2.16	6.10	16.01	0.83	19.27
Churchill	BrL10	Lower	5.30	1.92	6.35	15.81	0.62	25.71
Churchill	BrL11	Lower	6.00	1.63	6.41	16.22	0.65	24.99
Churchill	BrL12	Lower	5.10	1.35	6.35	11.62	0.54	21.68
Churchill	HW1	Wedge	5.00	2.79	5.14	45.55	3.09	14.74
Churchill	HW2	Wedge	5.70	1.56	5.91	35.43	2.34	15.14
Churchill	HW3	Wedge	5.20	2.69	5.91	46.47	3.12	14.89
Churchill	HW4	Wedge	5.80	1.44	6.05	32.41	1.99	16.29
Churchill	HW5	Wedge	6.90	2.37	6.32	38.07	2.94	12.95
Churchill	HW6	Wedge	5.10	2.98	6.14	43.60	3.33	13.09
Churchill	HW7	Wedge	4.50	2.80	5.95	44.78	3.06	14.63
Churchill	HW8	Wedge	5.00	2.32	6.06	43.57	3.31	13.16
Churchill	HW9	Wedge	6.20	2.75	6.01	44.24	3.39	13.05
Churchill	HW10	Wedge	6.80	2.60	5.98	42.93	3.27	13.13
Churchill	HW11	Wedge	6.40	2.74	5.97	43.85	3.25	13.49
Churchill	HW12	Wedge	7.40	1.53	6.33	30.71	1.81	16.97
Churchill	HW13	Wedge	5.80	0.81	6.27	23.15	0.92	25.08
Churchill	HW14	Wedge	5.60	1.41	6.16	33.20	2.34	14.19
Churchill	HW15	Wedge	6.80	2.60	6.17	43.00	3.05	14.10
Churchill	HP1	Hummock	7.40	2.25	3.81	45.15	3.07	14.71
Churchill	HP2	Hummock	7.20	1.70	4.04	47.61	1.61	29.57
Churchill	HP3	Hummock	7.20	2.37	4.20	48.87	1.30	37.59
Churchill	HP4	Hummock	7.20	2.46	4.58	46.17	1.77	26.08
Churchill	HP5	Hummock	7.80	2.34	4.45	46.16	2.33	19.81
Churchill	HP6	Hummock	7.80	2.11	3.66	48.63	1.09	44.61
Churchill	HP7	Hummock	7.30	2.47	3.85	48.75	1.04	46.88
Churchill	HP8	Hummock	6.10	2.10	3.67	48.26	0.66	72.79
Churchill	HP9	Hummock	7.30	2.36	3.50	48.76	1.05	46.44
Churchill	HP10	Hummock	8.90	2.41	4.68	45.69	2.29	19.95

Ecosystem	Point	Topo	T	Moisture	pH	SOC	TN	Soil C:N
			°C	g H_2O g^{-1}		g $100g^{-1}$	g $100g^{-1}$	
Churchill	HP11	Hummock	7.50	2.51	4.88	45.04	1.92	23.46
Churchill	HP12	Hummock	8.10	2.28	5.01	44.14	1.76	25.08
Churchill	HP13	Hummock	9.10	1.55	3.53	49.40	1.37	36.06
Churchill	HP14	Hummock	9.00	1.91	3.81	47.95	1.47	32.62
Churchill	HP15	Hummock	7.80	2.13	4.45	46.55	1.96	23.75
Daring Lake	Ua15	Up	14.00	0.48	4.53	3.79	0.18	21.16
Daring Lake	Ua10	Up	14.30	0.84	3.98	6.54	0.34	19.51
Daring Lake	Ua5	Up	13.90	0.28	4.34	2.29	0.15	15.29
Daring Lake	Ua0	Up	12.20	0.71	4.56	2.45	0.15	15.99
Daring Lake	Ba15	Back	10.70	0.50	4.13	3.20	0.10	32.80
Daring Lake	Ba10	Back	11.20	0.62	3.52	11.84	0.45	26.61
Daring Lake	Ba5	Back	12.90	0.42	4.16	2.52	0.07	37.06
Daring Lake	Ba0	Back	14.00	0.48	3.72	4.44	0.16	27.92
Daring Lake	La15	Low	13.30	1.02	3.58	8.96	0.37	24.55
Daring Lake	La10	Low	14.40	3.39	3.40	42.75	1.60	26.72
Daring Lake	La5	Low	13.10	0.60	3.72	4.04	0.13	30.13
Daring Lake	La0	Low	14.50	3.76	3.26	36.61	1.23	29.76
Daring Lake	Ub15	Up	11.40	0.97	4.16	3.79	0.16	24.29
Daring Lake	Ub10	Up	12.00	0.39	3.77	8.19	0.36	22.94
Daring Lake	Ub5	Up	11.80	0.41	4.17	2.95	0.15	20.19
Daring Lake	Ub0	Up	12.10	0.43	4.30	1.99	0.11	17.73
Daring Lake	Bb15	Back	11.90	0.73	3.30	23.28	0.85	27.45
Daring Lake	Bb10	Back	11.30	0.95	3.20	12.22	0.52	23.45
Daring Lake	Bb5	Back	12.70	0.32	4.06	1.89	0.05	34.99
Daring Lake	Bb0	Back	13.30	0.50	3.96	1.66	0.07	25.29
Daring Lake	Lb15	Low	13.50	0.26	4.13	3.22	0.09	34.20
Daring Lake	Lb10	Low	13.90	1.26	3.45	15.45	0.52	29.54
Daring Lake	Lb5	Low	15.20	0.38	4.22	3.04	0.06	53.31
Daring Lake	Lb0	Low	12.60	3.39	3.28	42.66	1.29	33.07
Daring Lake	Uc15	Up	16.00	0.53	4.16	6.27	0.30	20.68
Daring Lake	Uc10	Up	15.10	0.44	4.03	7.31	0.36	20.60
Daring Lake	Uc5	Up	14.90	1.01	3.76	13.30	0.67	19.97
Daring Lake	Uc0	Up	15.70	0.38	4.43	2.03	0.09	22.98
Daring Lake	Bc15	Back	16.10	0.31	3.96	2.56	0.10	25.38
Daring Lake	Bc10	Back	15.20	0.82	3.80	9.30	0.37	25.48
Daring Lake	Bc5	Back	14.60	0.39	3.95	1.87	0.09	20.13
Daring Lake	Bc0	Back	14.80	0.40	4.05	1.68	0.05	33.36
Daring Lake	Lc15	Low	14.40	0.36	4.39	1.15	0.02	52.94
Daring Lake	Lc10	Low	13.20	0.87	4.29	3.92	0.12	33.50
Daring Lake	Lc5	Low	14.90	3.98	3.21	44.73	1.34	33.38
Daring Lake	Lc0	Low	12.50	4.62	3.35	41.24	1.25	32.99
Daring Lake	Ud15	Up	10.70	0.40	4.37	3.89	0.23	16.86
Daring Lake	Ud10	Up	11.30	0.31	4.42	3.70	0.22	16.60
Daring Lake	Ud5	Up	11.20	0.57	4.35	2.21	0.16	13.92
Daring Lake	Ud0	Up	11.90	0.36	4.52	1.99	0.09	22.26

Ecosystem	Point	Topo	T	Moisture	pH	SOC	TN	Soil C:N
			°C	g H_2O g^{-1}		g $100g^{-1}$	g $100g^{-1}$	
Daring Lake	Bd15	Back	11.60	0.77	3.34	6.94	0.26	26.68
Daring Lake	Bd10	Back	11.90	1.50	3.18	32.17	1.48	21.74
Daring Lake	Bd5	Back	11.60	0.48	3.76	2.71	0.11	24.88
Daring Lake	Bd0	Back	12.50	0.33	4.03	2.32	0.07	31.65
Daring Lake	Ld15	Low	12.00	3.74	3.37	42.62	1.51	28.23
Daring Lake	Ld10	Low	11.70		3.35	45.18	1.41	32.04
Daring Lake	Ld5	Low	12.40	3.26	3.42	42.22	1.54	27.42
Daring Lake	Ld0	Low	11.60	3.02	3.55	43.05	1.45	29.69
Daring Lake	Ue15	Up	15.50	0.30	4.40	3.94	0.21	18.67
Daring Lake	Ue10	Up	15.70	0.43	4.07	6.22	0.33	18.67
Daring Lake	Ue5	Up	15.80	0.32	4.40	3.20	0.16	19.77
Daring Lake	Ue0	Up	15.90	0.40	4.72	1.68	0.08	21.96
Daring Lake	Be15	Back	13.10	0.43	3.48	6.10	0.22	27.61
Daring Lake	Be10	Back	14.40	0.32	4.22	3.45	0.09	36.60
Daring Lake	Be5	Back	13.40	0.63	3.69	6.65	0.29	22.92
Daring Lake	Be0	Back	13.90	0.42	3.65	7.47	0.29	25.84
Daring Lake	Le15	Low	13.00	3.29	3.31	38.95	1.48	26.32
Daring Lake	Le10	Low	12.90	1.09	3.50	10.28	0.36	28.32
Daring Lake	Le5	Low	14.30	3.91	3.13	44.59	1.40	31.85
Daring Lake	Le0	Low	14.50	1.02	4.33	1.95	0.06	31.43
Truelove	TU1	Up	17.70	0.35	5.98	21.58	1.37	15.75
Truelove	TU2	Up	15.60	0.50	6.33	23.03	1.67	13.79
Truelove	TU3	Up	16.90	0.43	6.35	14.93	1.07	13.95
Truelove	TU4	Up	12.50	1.05	6.35	24.21	1.90	12.74
Truelove	TU5	Up	16.60	1.22	6.36	31.79	2.06	15.43
Truelove	TU6	Up	12.50	0.80	6.33	34.30	2.01	17.06
Truelove	TU7	Up	18.70	0.35	6.41	26.00	1.87	13.90
Truelove	TU8	Up	15.10	0.21	6.40	11.16	0.85	13.10
Truelove	TU9	Up	13.70	0.41	6.47	30.65	1.63	18.80
Truelove	TU10	Up	15.00	0.32	6.48	18.18	1.27	14.32
Truelove	TB1	Back	11.00	1.44	6.47	30.36	2.13	14.25
Truelove	TB2	Back	10.60	0.93	6.51	18.30	1.49	12.28
Truelove	TB3	Back	11.70	1.17	6.49	25.28	1.81	13.97
Truelove	TB4	Back	9.70	1.00	6.54	22.76	1.78	12.79
Truelove	TB5	Back	14.20	1.32	6.53	22.93	1.63	14.07
Truelove	TB6	Back	14.30	1.77	6.48	29.53	2.01	14.69
Truelove	TB7	Back	13.50	0.98	6.48	24.27	1.94	12.51
Truelove	TB8	Back	12.40	1.30	6.51	26.58	1.92	13.84
Truelove	TB9	Back	11.60	1.49	6.49	26.69	1.77	15.08
Truelove	TB10	Back	12.30	1.69	6.49	27.10	1.98	13.69
Truelove	TL1	Low	8.00	1.89	6.48	28.72	2.21	13.00
Truelove	TL2	Low	9.50	1.30	6.50	15.61	1.11	14.06
Truelove	TL3	Low	9.50	1.33	6.51	16.58	1.17	14.17
Truelove	TL4	Low	9.20	0.31	6.50	2.86	0.14	20.02
Truelove	TL5	Low	12.30	1.21	6.52	12.76	1.06	12.04

Ecosystem	Point	Topo	T	Moisture	pH	SOC	TN	Soil C:N
			°C	g H_2O g^{-1}		g $100g^{-1}$	g $100g^{-1}$	
Truelove	TL6	Low	11.30	0.70	6.54	8.03	0.53	15.18
Truelove	TL7	Low	8.40	2.52	6.55	28.97	1.99	14.56
Truelove	TL8	Low	7.70	2.50	6.53	27.02	1.92	14.07
Truelove	TL9	Low	9.90	3.61	6.22	30.58	1.59	19.23
Truelove	TL10	Low	8.40	6.98	6.19	40.74	2.57	15.85
Truelove	W1.1	Wedge	11.60	1.59	5.28	32.54	2.04	15.95
Truelove	W1.2	Wedge	13.00	1.51	5.37	31.90	2.04	15.64
Truelove	W2.1	Wedge	11.30	1.75	5.62	36.10	2.11	17.11
Truelove	W2.2	Wedge	12.40	2.07	5.72	31.18	2.00	15.59
Truelove	W3	Wedge	11.20	1.34	5.56	28.89	2.05	14.09
Truelove	W4	Wedge	14.80	0.51	5.68	44.50	2.00	22.25
Truelove	W5	Wedge	12.90	1.44	5.80	24.65	1.86	13.25
Truelove	W6	Wedge	11.20	0.88	5.79	40.74	2.11	19.31
Truelove	W7	Wedge	10.90	1.69	5.86	29.81	1.93	15.45
Truelove	W8	Wedge	9.20	1.33	5.90	28.85	1.91	15.10
Truelove	W9	Wedge	13.60	1.57	5.88	27.01	1.86	14.52
Truelove	W10	Wedge	10.10	2.43	5.77	42.65	1.78	23.96
Truelove	P1.1	Hummock	10.70	1.29	6.00	30.68	2.05	14.97
Truelove	P1.2	Hummock	11.60	1.07	5.96	30.07	2.09	14.39
Truelove	P2.1	Hummock	14.80	0.63	5.58	31.55	2.18	14.47
Truelove	P2.2	Hummock	13.60	0.52	5.71	31.15	2.11	14.76
Truelove	P3	Hummock	14.50	0.38	6.04	30.03	2.08	14.44
Truelove	P4	Hummock	13.40	1.22	6.00	30.45	2.05	14.85
Truelove	P5	Hummock	14.70	0.95	6.12	30.24	2.17	13.94
Truelove	P6	Hummock	11.00	1.01	6.02	27.43	1.96	13.99
Truelove	P7	Hummock	11.40	1.24	6.13	28.29	1.96	14.43
Truelove	P8	Hummock	11.10	1.21	6.25	29.45	2.04	14.44
Truelove	P9	Hummock	10.90	1.07	6.26	27.65	2.04	13.55
Truelove	P10	Hummock	12.40	0.94	6.05	30.07	2.21	13.61

Table F 3: Water-extractable OM.

Ecosystem	Point	Topo	WSOC	WSON	WEOM C:N	$N\text{-}NH_4^+$	$N\text{-}NO_3^-$
			ug g^{-1}	ug g^{-1}		ug g^{-1}	ug g^{-1}
Churchill	DU1	Upper	11.79	0.35	10.95	0.30	0.40
Churchill	DU2	Upper	12.83	0.13	13.82	0.15	0.20
Churchill	DU3	Upper	92.39	3.62	14.59	1.27	0.08
Churchill	DU4	Upper	21.79	0.44	14.75	0.08	0.22
Churchill	DU5	Upper	31.27	1.06	15.57	0.13	0.05
Churchill	DU6	Upper	24.52	1.02	13.79	0.06	0.00
Churchill	DU7	Upper	34.60	0.63	14.79	0.00	0.20
Churchill	DU8	Upper	27.13	-0.01	15.83	0.00	0.17
Churchill	DU9	Upper	62.23	1.02	16.95	0.00	0.00
Churchill	DU10	Upper	22.87	0.36	14.44	0.07	0.34
Churchill	DU11	Upper	14.09	-0.43	15.93	0.03	0.29
Churchill	DU12	Upper	66.18	1.77	16.72	0.23	0.00
Churchill	DB1	Back	78.92	2.88	13.73	1.58	0.00
Churchill	DB2	Back	62.31	-2.04	20.83	0.31	0.00
Churchill	DB3	Back	536.76	19.39	15.42	5.32	4.70
Churchill	DB4	Back	206.62	11.75	13.46	1.12	0.00
Churchill	DB5	Back	118.73	1.19	22.43	0.00	0.00
Churchill	DB6	Back	107.23	3.63	16.41	0.13	0.49
Churchill	DB7	Back	97.56	2.07	21.07	0.00	0.00
Churchill	DB8	Back	84.55	1.66	18.26	0.00	0.00
Churchill	DB9	Back	163.91	6.53	14.87	2.25	1.19
Churchill	DB10	Back	178.14	7.05	19.06	0.13	0.00
Churchill	DB11	Back	85.06	0.83	17.65	0.70	0.03
Churchill	DB12	Back	175.27	3.22	21.37	0.39	0.00
Churchill	DL1	Lower	224.79	8.92	14.61	6.35	0.00
Churchill	DL2	Lower	168.47	-4.14	22.23	0.38	0.00
Churchill	DL3	Lower	104.95	0.31	20.09	0.27	0.00
Churchill	DL4	Lower	632.83	22.48	24.11	0.00	0.00
Churchill	DL5	Lower	228.69	7.92	18.77	0.63	0.00
Churchill	DL6	Lower	346.41	5.36	25.79	0.00	0.00
Churchill	DL7	Lower	136.42	3.48	18.18	0.00	0.00
Churchill	DL8	Lower	273.51	4.76	24.28	0.00	0.00
Churchill	DL9	Lower	164.51	1.77	23.03	0.00	0.00
Churchill	DL10	Lower	143.79	4.98	16.63	1.65	0.00
Churchill	DL11	Lower	571.00	14.82	26.56	1.15	0.00
Churchill	DL12	Lower	293.97	5.39	25.97	0.39	0.00
Churchill	BgU1	Upper	51.46	1.28	19.44	0.22	0.00
Churchill	BgU2	Upper	37.46	0.64	18.63	0.18	0.00
Churchill	BgU3	Upper	30.58	1.36	16.35	0.04	0.05
Churchill	BgU4	Upper	18.66	0.15	18.95	0.00	0.00
Churchill	BgU5	Upper	19.07	0.16	18.57	0.00	0.00
Churchill	BgU6	Upper	14.60	0.39	15.37	0.00	0.00
Churchill	BgU7	Upper	90.03	4.62	15.92	0.67	0.00

Ecosystem	Point	Topo	WSOC	WSON	WEOM C:N	$N\text{-}NH_4^+$	$N\text{-}NO_3^-$
			ug g^{-1}	ug g^{-1}		ug g^{-1}	ug g^{-1}
Churchill	BgU8	Upper	6.92	0.01	15.49	0.00	0.00
Churchill	BgU9	Upper	6.32	-0.38	18.81	0.00	0.00
Churchill	BgU10	Upper	74.24	3.09	17.82	0.73	0.00
Churchill	BgU11	Upper	53.65	5.60	10.77	0.45	0.00
Churchill	BgU12	Upper	5.55	-0.26	17.88	0.00	0.11
Churchill	BgB1	Back	43.88	0.54	19.56	0.00	0.00
Churchill	BgB2	Back	61.08	0.47	22.03	0.00	0.00
Churchill	BgB3	Back	71.08	-1.72	23.76	0.00	0.00
Churchill	BgB4	Back	145.43	1.00	20.34	0.00	0.00
Churchill	BgB5	Back	57.44	-0.05	20.66	0.00	0.00
Churchill	BgB6	Back	336.90	3.04	23.55	0.00	0.00
Churchill	BgB7	Back	284.18	-0.59	26.16	0.00	0.00
Churchill	BgB8	Back	213.09	-2.95	22.57	0.00	0.00
Churchill	BgB9	Back	126.76	0.66	21.14	0.00	0.00
Churchill	BgB10	Back	25.96	-0.41	20.14	0.00	0.00
Churchill	BgB11	Back	22.13	-0.83	22.78	0.00	0.00
Churchill	BgB12	Back	54.67	1.17	19.64	0.00	0.00
Churchill	BgL1	Lower	353.81	-11.76	23.10	0.30	0.00
Churchill	BgL2	Lower	160.71	3.43	17.08	0.00	0.00
Churchill	BgL3	Lower	130.88	-4.35	22.10	0.00	0.00
Churchill	BgL4	Lower	92.17	-5.94	21.36	0.00	0.00
Churchill	BgL5	Lower	58.00	-10.21	24.17	0.00	0.00
Churchill	BgL6	Lower	140.17	2.01	16.92	0.00	0.48
Churchill	BgL7	Lower	153.82	-2.11	17.35	4.44	0.00
Churchill	BgL8	Lower	141.40	-9.69	24.94	0.00	0.00
Churchill	BgL9	Lower	222.54	2.65	19.92	0.70	0.00
Churchill	BgL10	Lower	114.03	-1.27	17.29	2.44	0.00
Churchill	BgL11	Lower	141.49	-2.21	18.69	1.29	0.63
Churchill	BgL12	Lower	311.07	-9.02	20.06	1.53	0.00
Churchill	BrU1	Upper	8.30	0.21	13.64	0.00	0.00
Churchill	BrU2	Upper	8.34	0.38	12.71	0.00	0.00
Churchill	BrU3	Upper	62.39	2.64	16.68	0.21	0.00
Churchill	BrU4	Upper	33.47	1.10	16.10	0.00	0.00
Churchill	BrU5	Upper	11.26	-0.20	18.06	0.00	0.00
Churchill	BrU6	Upper	12.59	-0.14	18.42	0.00	0.00
Churchill	BrU7	Upper	48.00	-0.32	45.66	0.00	0.00
Churchill	BrU8	Upper	8.85	-0.35	20.39	0.00	0.01
Churchill	BrU9	Upper	27.22	0.17	21.23	0.00	0.02
Churchill	BrU10	Upper	8.04	-0.04	15.23	0.00	0.00
Churchill	BrU11	Upper	11.48	0.03	16.22	0.00	0.00
Churchill	BrU12	Upper	56.91	1.62	19.30	0.00	0.00
Churchill	BrB1	Back	11.25	0.24	15.80	0.00	0.00
Churchill	BrB2	Back	34.42	0.83	15.51	0.04	0.00
Churchill	BrB3	Back	61.58	1.11	22.46	0.00	0.00
Churchill	BrB4	Back	17.60	0.50	14.19	0.01	0.00

Ecosystem	Point	Topo	WSOC	WSON	WEOM C:N	$N\text{-}NH_4^+$	$N\text{-}NO_3^-$
			ug g^{-1}	ug g^{-1}		ug g^{-1}	ug g^{-1}
Churchill	BrB5	Back	178.58	6.63	20.10	0.00	0.00
Churchill	BrB6	Back	18.07	0.26	18.32	0.00	0.00
Churchill	BrB7	Back	39.95	1.63	17.40	0.00	0.00
Churchill	BrB8	Back	15.88	-0.05	20.24	0.00	0.00
Churchill	BrB9	Back	16.14	0.18	18.77	0.00	0.00
Churchill	BrB10	Back	19.03	0.35	19.78	0.00	0.00
Churchill	BrB11	Back	26.27	0.28	21.05	0.00	0.00
Churchill	BrB12	Back	26.67	0.37	20.60	0.00	0.00
Churchill	BrL1	Lower	194.85	5.35	17.43	3.46	0.00
Churchill	BrL2	Lower	60.30	0.33	18.07	0.36	0.00
Churchill	BrL3	Lower	698.62	19.35	19.59	13.01	0.00
Churchill	BrL4	Lower	45.48	0.94	17.48	0.15	0.00
Churchill	BrL5	Lower	25.84	1.02	13.55	0.52	0.00
Churchill	BrL6	Lower	22.14	0.87	14.31	0.12	0.00
Churchill	BrL7	Lower	21.70	-0.59	17.99	0.00	0.00
Churchill	BrL8	Lower	23.36	-1.01	19.11	0.00	0.00
Churchill	BrL9	Lower	6.53	-0.45	14.37	0.07	0.00
Churchill	BrL10	Lower	141.01	1.78	26.48	0.05	0.00
Churchill	BrL11	Lower	53.04	0.30	18.67	0.37	0.00
Churchill	BrL12	Lower	26.02	0.65	14.66	1.09	0.00
Churchill	HW1	Wedge	95.25	3.13	18.07	0.00	0.00
Churchill	HW2	Wedge	94.16	4.49	15.90	0.69	0.38
Churchill	HW3	Wedge	118.51	4.80	16.71	0.57	0.00
Churchill	HW4	Wedge	37.64	0.72	16.64	0.37	0.07
Churchill	HW5	Wedge	64.32	2.43	16.83	0.00	0.22
Churchill	HW6	Wedge	218.36	6.26	19.49	0.00	0.00
Churchill	HW7	Wedge	346.74	10.63	21.58	0.00	0.00
Churchill	HW8	Wedge	577.35	32.04	17.94	1.32	0.00
Churchill	HW9	Wedge	104.84	2.61	16.69	0.00	1.43
Churchill	HW10	Wedge	222.54	8.08	16.97	3.37	0.40
Churchill	HW11	Wedge	122.65	4.48	18.30	0.00	0.00
Churchill	HW12	Wedge	48.15	1.51	14.87	1.18	0.33
Churchill	HW13	Wedge	304.10	18.11	17.15	0.96	0.00
Churchill	HW14	Wedge	74.90	1.76	18.68	0.00	0.00
Churchill	HW15	Wedge	101.55	3.70	15.08	1.39	1.17
Churchill	HP1	Hummock	78.26	-1.11	21.36	0.00	0.00
Churchill	HP2	Hummock	70.38	-1.01	22.72	0.00	0.00
Churchill	HP3	Hummock	114.59	-5.15	26.57	0.00	0.00
Churchill	HP4	Hummock	47.09	-1.07	19.06	0.00	0.00
Churchill	HP5	Hummock	99.14	0.42	19.11	0.00	0.00
Churchill	HP6	Hummock	45.24	-3.88	22.31	0.00	0.00
Churchill	HP7	Hummock	76.75	-2.93	21.91	0.00	0.00
Churchill	HP8	Hummock	62.82	-3.57	25.40	0.00	0.00
Churchill	HP9	Hummock	70.13	-5.34	22.41	0.00	0.00
Churchill	HP10	Hummock	64.11	-1.65	20.50	0.00	0.00

Ecosystem	Point	Topo	WSOC	WSON	WEOM C:N	$N\text{-}NH_4^+$	$N\text{-}NO_3^-$
			ug g^{-1}	ug g^{-1}		ug g^{-1}	ug g^{-1}
Churchill	HP11	Hummock	106.35	0.63	22.18	0.00	0.00
Churchill	HP12	Hummock	142.38	0.03	22.36	0.00	0.00
Churchill	HP13	Hummock	59.80	-1.68	25.10	0.00	0.00
Churchill	HP14	Hummock	93.99	-1.41	27.22	0.00	0.00
Churchill	HP15	Hummock	91.34	-2.28	25.28	0.00	0.00
Daring Lake	Ua15	Up	16.46	0.76	29.15	0.00	0.02
Daring Lake	Ua10	Up	72.32	2.00	43.15	0.00	0.05
Daring Lake	Ua5	Up	12.23	0.41	43.74	0.00	0.01
Daring Lake	Ua0	Up	8.53	0.51	26.81	0.04	0.04
Daring Lake	Ba15	Back	63.27	1.96	35.93	0.00	0.02
Daring Lake	Ba10	Back	228.69	4.01	58.88	0.08	0.18
Daring Lake	Ba5	Back	25.31	0.48	62.81	0.00	0.01
Daring Lake	Ba0	Back	107.49	1.85	62.26	0.00	0.03
Daring Lake	La15	Low	98.50	3.37	30.29	0.34	0.11
Daring Lake	La10	Low	462.22	10.33	50.32	0.00	0.14
Daring Lake	La5	Low	53.40	0.86	68.49	0.00	0.02
Daring Lake	La0	Low	594.03	9.96	63.00	0.00	0.45
Daring Lake	Ub15	Up	24.91	0.90	34.03	0.00	0.02
Daring Lake	Ub10	Up			43.03		
Daring Lake	Ub5	Up	10.85	0.33	47.13	0.00	0.01
Daring Lake	Ub0	Up	5.67	0.24	39.08	0.00	0.01
Daring Lake	Bb15	Back	97.17	1.93	55.54	0.00	0.02
Daring Lake	Bb10	Back	40.15	0.78	61.61	0.00	0.02
Daring Lake	Bb5	Back			84.22		
Daring Lake	Bb0	Back	27.46	0.73	46.47	0.02	0.01
Daring Lake	Lb15	Low	25.58	0.48	63.67	0.00	0.01
Daring Lake	Lb10	Low			58.80		
Daring Lake	Lb5	Low	22.23	0.39	67.40	0.00	0.01
Daring Lake	Lb0	Low	513.29	3.74	71.05	4.10	0.32
Daring Lake	Uc15	Up	26.10	0.73	45.00	0.06	0.01
Daring Lake	Uc10	Up	17.93	0.81	33.21	0.00	0.04
Daring Lake	Uc5	Up	118.52	2.20	65.33	0.00	0.00
Daring Lake	Uc0	Up	25.73	0.55	57.18	0.05	0.00
Daring Lake	Bc15	Back	34.23	0.73	59.35	0.00	0.00
Daring Lake	Bc10	Back	83.96	1.44	70.05	0.00	0.01
Daring Lake	Bc5	Back	45.70	1.09	52.93	0.00	0.00
Daring Lake	Bc0	Back	24.55	0.45	68.93	0.00	0.00
Daring Lake	Lc15	Low	17.21	0.28	83.30	0.00	0.00
Daring Lake	Lc10	Low	46.39	0.58	96.27	0.00	0.00
Daring Lake	Lc5	Low	702.31	11.56	69.04	0.06	0.00
Daring Lake	Lc0	Low	936.55	12.34	87.52	0.00	0.24
Daring Lake	Ud15	Up	23.68	0.72	47.23	0.15	0.00
Daring Lake	Ud10	Up	15.22	0.47	42.63	0.02	0.00
Daring Lake	Ud5	Up	16.05	0.41	56.40	0.00	0.00
Daring Lake	Ud0	Up	22.96	0.00		0.00	0.00

Ecosystem	Point	Topo	WSOC	WSON	WEOM C:N	$N\text{-}NH_4^+$	$N\text{-}NO_3^-$
			ug g^{-1}	ug g^{-1}		ug g^{-1}	ug g^{-1}
Daring Lake	Bd15	Back			74.20		
Daring Lake	Bd10	Back	341.93	6.38	60.87	0.08	0.03
Daring Lake	Bd5	Back	46.84	0.79	74.25	0.00	0.00
Daring Lake	Bd0	Back	44.61	0.63	83.74	0.02	0.00
Daring Lake	Ld15	Low	536.49	8.52	78.26	0.22	0.01
Daring Lake	Ld10	Low				0.00	0.49
Daring Lake	Ld5	Low	994.99	16.28	79.01	0.00	0.40
Daring Lake	Ld0	Low	806.60	8.72	106.97	0.00	0.05
Daring Lake	Ue15	Up	13.34	0.40	48.41	0.04	0.00
Daring Lake	Ue10	Up	26.04	0.63	53.90	0.01	0.01
Daring Lake	Ue5	Up	18.00	0.40	64.08	0.00	0.01
Daring Lake	Ue0	Up	5.91	0.00		0.00	0.00
Daring Lake	Be15	Back	99.62	2.54	51.23	0.00	0.00
Daring Lake	Be10	Back	34.79	0.42	107.32	0.00	0.00
Daring Lake	Be5	Back	123.88	3.28	46.65	0.00	0.00
Daring Lake	Be0	Back	156.03	3.29	56.14	0.00	0.01
Daring Lake	Le15	Low	637.08	14.75	54.50	0.13	0.50
Daring Lake	Le10	Low	113.60	2.45	58.45	0.00	0.00
Daring Lake	Le5	Low	851.07	16.39	63.90	0.00	0.00
Daring Lake	Le0	Low	29.07	0.09	93.71	0.35	0.00
Truelove	TU1	Up	122.92	8.34	13.70	0.59	0.59
Truelove	TU2	Up	93.26	3.85	22.46	0.38	0.07
Truelove	TU3	Up	119.76	3.99	28.81	0.22	0.05
Truelove	TU4	Up	83.77	4.98	16.23	0.44	0.09
Truelove	TU5	Up	93.02	2.93	27.63	0.43	0.09
Truelove	TU6	Up	231.96	7.71	29.44	0.25	0.09
Truelove	TU7	Up	237.62	10.81	19.66	1.58	0.13
Truelove	TU8	Up	90.06	3.74	22.39	0.15	0.31
Truelove	TU9	Up	250.73	9.14	25.67	0.87	0.05
Truelove	TU10	Up	114.88	5.13	19.15	1.03	0.07
Truelove	TB1	Back	58.77	3.05	20.27	0.00	0.18
Truelove	TB2	Back	49.26	2.17	23.73	0.00	0.10
Truelove	TB3	Back	72.19	3.26	21.29	0.35	0.11
Truelove	TB4	Back	46.87	2.18	22.56	0.00	0.10
Truelove	TB5	Back	37.86	2.54	15.93	0.05	0.21
Truelove	TB6	Back	66.00	3.71	18.54	0.06	0.26
Truelove	TB7	Back	59.77	4.01	15.41	0.28	0.12
Truelove	TB8	Back	107.10	8.06	14.00	0.44	0.16
Truelove	TB9	Back	123.58	6.22	20.30	0.39	0.09
Truelove	TB10	Back	147.93	14.53	10.34	1.24	0.26
Truelove	TL1	Low	72.47	4.46	17.60	0.00	0.07
Truelove	TL2	Low	76.02	4.11	16.45	0.93	0.04
Truelove	TL3	Low	59.72	3.25	19.71	0.00	0.07
Truelove	TL4	Low	19.97	0.64	29.13	0.07	0.00
Truelove	TL5	Low	39.11	2.55	13.26	0.73	0.07

Ecosystem	Point	Topo	WSOC	WSON	WEOM C:N	$N\text{-}NH_4^+$	$N\text{-}NO_3^-$
			ug g^{-1}	ug g^{-1}		ug g^{-1}	ug g^{-1}
Truelove	TL6	Low	17.64	1.10	14.79	0.22	0.04
Truelove	TL7	Low	95.22	5.13	18.94	0.30	0.06
Truelove	TL8	Low	73.95	4.33	16.12	0.71	0.02
Truelove	TL9	Low	149.84	9.34	10.17	7.40	0.04
Truelove	TL10	Low	216.96	11.79	7.72	22.20	1.04
Truelove	W1.1	Wedge	261.74	14.15	16.86	2.44	0.01
Truelove	W1.2	Wedge	586.80		16.12		
Truelove	W2.1	Wedge	212.26		13.84		
Truelove	W2.2	Wedge	169.59	10.45	13.32	3.15	0.27
Truelove	W3	Wedge	193.63	11.97	17.08	0.13	0.08
Truelove	W4	Wedge	253.84	16.95	11.62	6.32	0.37
Truelove	W5	Wedge	153.53	8.48	17.89	0.36	0.31
Truelove	W6	Wedge	255.45	17.16	7.87	17.38	1.67
Truelove	W7	Wedge	314.75		15.61		
Truelove	W8	Wedge	153.07	8.22	19.63	0.06	0.03
Truelove	W9	Wedge	102.29	6.29	16.12	0.16	0.49
Truelove	W10	Wedge	878.27	44.83	15.58	13.99	0.92
Truelove	P1.1	Hummock	201.66	8.87	22.81	0.32	0.17
Truelove	P1.2	Hummock	403.47	18.50	22.31	0.26	0.28
Truelove	P2.1	Hummock	385.20	26.58	12.42	5.76	0.70
Truelove	P2.2	Hummock	223.20	13.72	15.09	1.87	0.15
Truelove	P3	Hummock	585.73	33.52	17.37	1.74	0.27
Truelove	P4	Hummock	200.26	10.45	20.04	0.19	0.06
Truelove	P5	Hummock	123.16	7.68	16.86	0.11	0.07
Truelove	P6	Hummock	256.76	14.13	16.58	2.33	0.16
Truelove	P7	Hummock	92.63	7.17	12.95	0.15	0.70
Truelove	P8	Hummock	193.67	10.39	17.37	1.46	0.09
Truelove	P9	Hummock	160.39	7.61	21.31	0.12	0.27
Truelove	P10	Hummock	358.24	20.06	14.39	6.17	0.32

Table F 4: Density fractions of SOM.

Ecosystem	Point	Topo	LF Qty	C-LF	N-LF	LF C:N	C-HF	N-HF	HF C:N
			g g^{-1}	g $100g^{-1}$	g $100g^{-1}$		g $100g^{-1}$	g $100g^{-1}$	
Churchill	DU1	Upper	0.02	0.58	0.03	22.89	6.33	0.16	40.79
Churchill	DU2	Upper	0.02	0.68	0.02	27.50	6.33	0.16	39.12
Churchill	DU3	Upper	0.04	1.88	0.08	22.83	5.56	0.24	22.75
Churchill	DU4	Upper	0.01	0.51	0.02	21.48	6.02	0.18	33.57
Churchill	DU5	Upper	0.01	0.43	0.02	24.55	5.79	0.13	43.13
Churchill	DU6	Upper	0.04	1.45	0.06	24.04	5.54	0.25	22.19
Churchill	DU7	Upper	0.01	0.55	0.02	25.47	5.59	0.16	35.90
Churchill	DU8	Upper	0.03	1.20	0.05	25.96	4.41	0.12	36.35
Churchill	DU9	Upper	0.02	0.58	0.03	21.93	5.26	0.31	16.90
Churchill	DU10	Upper	0.03	1.04	0.04	23.16	5.44	0.20	27.54
Churchill	DU11	Upper	0.01	0.31	0.01	24.81	5.97	0.15	40.64
Churchill	DU12	Upper	0.06	2.35	0.10	24.59	6.07	0.29	21.02
Churchill	DB1	Back	0.06	2.45	0.09	27.97	5.63	0.19	29.54
Churchill	DB2	Back	0.62	27.24	0.65	41.81	15.10	0.59	25.51
Churchill	DB3	Back	0.62	28.08	1.03	27.27	16.16	0.85	19.02
Churchill	DB4	Back	0.11	4.47	0.14	32.33	12.09	0.50	24.40
Churchill	DB5	Back	0.24	10.28	0.40	25.94	17.28	1.07	16.13
Churchill	DB6	Back	0.27	10.61	0.49	21.58	28.25	2.02	13.99
Churchill	DB7	Back	0.10	4.09	0.11	37.17	11.50	0.54	21.42
Churchill	DB8	Back	0.18	7.59	0.28	27.57	17.62	0.88	19.93
Churchill	DB9	Back	0.26	11.28	0.59	19.16	25.30	1.71	14.84
Churchill	DB10	Back	0.06	2.67	0.10	28.10	8.30	0.41	20.32
Churchill	DB11	Back	0.51	22.25	0.73	30.42	18.63	1.04	17.86
Churchill	DB12	Back	0.56	24.13	0.94	25.63	15.65	1.07	14.58
Churchill	DL1	Lower	0.47	20.48	0.77	26.69	22.75	1.25	18.22
Churchill	DL2	Lower	0.74	33.04	0.84	39.47	11.62	0.47	24.62
Churchill	DL3	Lower	0.39	17.16	0.75	22.81	25.33	1.73	14.61
Churchill	DL4	Lower	0.75	32.66	0.92	35.37	10.89	0.48	22.76
Churchill	DL5	Lower	0.52	23.05	1.28	18.04	20.71	1.51	13.70
Churchill	DL6	Lower	0.51	22.29	0.98	22.79	20.61	1.43	14.45
Churchill	DL7	Lower	0.62	28.11	1.62	17.38	16.35	1.18	13.90
Churchill	DL8	Lower	0.74	32.75	1.70	19.22	11.34	0.77	14.65
Churchill	DL9	Lower	0.75	34.30	2.06	16.62	10.51	0.74	14.20
Churchill	DL10	Lower	0.91	40.19	2.67	15.07	3.88	0.28	13.71
Churchill	DL11	Lower	0.69	30.18	0.99	30.42	13.68	0.66	20.75
Churchill	DL12	Lower	0.55	23.95	0.97	24.72	18.95	1.23	15.39
Churchill	BgU1	Upper	0.04	1.71	0.07	24.10	4.53	0.20	22.77
Churchill	BgU2	Upper	0.06	2.38	0.09	25.39	3.85	0.18	21.83
Churchill	BgU3	Upper	0.01	0.23	0.01	34.98	1.75	0.06	29.11
Churchill	BgU4	Upper	0.01	0.34	0.01	28.33	1.41	0.06	24.95
Churchill	BgU5	Upper	0.03	1.34	0.06	21.12	5.08	0.23	22.04
Churchill	BgU6	Upper	0.03	1.19	0.05	24.62	4.40	0.12	36.78
Churchill	BgU7	Upper	0.01	0.37	0.01	32.54	1.79	0.07	27.30

Ecosystem	Point	Topo	LF Qty	C-LF	N-LF	LF C:N	C-HF	N-HF	HF C:N
			g g^{-1}	g $100g^{-1}$	g $100g^{-1}$		g $100g^{-1}$	g $100g^{-1}$	
Churchill	BgU8	Upper	0.01	0.30	0.01	24.07	1.02	0.04	24.89
Churchill	BgU9	Upper	0.01	0.48	0.02	23.70	2.05	0.09	23.13
Churchill	BgU10	Upper	0.01	0.53	0.02	29.09	2.96	0.07	39.91
Churchill	BgU11	Upper	0.03	1.30	0.05	27.86	2.03	0.07	28.67
Churchill	BgU12	Upper	0.00	0.00	0.00	29.75	1.33	0.02	64.56
Churchill	BgB1	Back	0.08	3.21	0.10	33.49	5.69	0.25	22.89
Churchill	BgB2	Back	0.06	2.30	0.07	32.94	6.02	0.19	31.37
Churchill	BgB3	Back	0.04	1.48	0.05	32.70	17.72	0.60	29.38
Churchill	BgB4	Back	0.24	9.86	0.35	28.36	15.29	0.61	24.99
Churchill	BgB5	Back	0.05	1.90	0.06	33.08	6.66	0.23	28.56
Churchill	BgB6	Back	0.48	20.23	0.72	27.93	21.28	1.03	20.58
Churchill	BgB7	Back	0.68	26.69	0.65	41.29	12.50	0.40	31.25
Churchill	BgB8	Back	0.30	11.53	0.42	27.36	22.96	0.97	23.63
Churchill	BgB9	Back	0.10	3.88	0.13	30.65	20.17	0.86	23.44
Churchill	BgB10	Back	0.12	4.55	0.15	29.47	18.81	0.66	28.50
Churchill	BgB11	Back	0.12	5.47	0.15	36.20	7.64	0.29	26.31
Churchill	BgB12	Back	0.04	1.48	0.04	33.93	10.84	0.53	20.36
Churchill	BgL1	Lower	0.27	8.50	0.22	38.74	18.07	0.76	23.62
Churchill	BgL2	Lower	0.37	13.48	0.48	27.91	20.90	1.23	17.05
Churchill	BgL3	Lower	0.29	9.86	0.44	22.29	26.39	1.82	14.50
Churchill	BgL4	Lower	0.39	14.74	0.59	25.00	22.74	1.60	14.19
Churchill	BgL5	Lower	0.04	1.43	0.04	37.27	25.24	1.66	15.19
Churchill	BgL6	Lower	0.24	8.06	0.30	26.77	22.90	1.65	13.88
Churchill	BgL7	Lower	0.20	7.50	0.43	17.63	29.49	2.33	12.65
Churchill	BgL8	Lower	0.39	15.44	0.61	25.16	23.95	1.55	15.48
Churchill	BgL9	Lower	0.39	14.81	0.49	30.08	24.77	1.41	17.53
Churchill	BgL10	Lower	0.23	9.15	0.44	20.84	29.67	2.17	13.68
Churchill	BgL11	Lower	0.33	12.09	0.64	18.82	24.63	1.74	14.12
Churchill	BgL12	Lower	0.73	28.73	0.89	32.30	10.36	0.45	23.05
Churchill	BrU1	Upper	0.02	0.65	0.03	22.58	2.40	0.08	30.14
Churchill	BrU2	Upper	0.04	1.63	0.06	29.00	1.79	0.08	23.17
Churchill	BrU3	Upper	0.05	1.80	0.08	23.45	2.62	0.10	25.42
Churchill	BrU4	Upper	0.02	0.99	0.04	22.54	3.68	0.11	33.35
Churchill	BrU5	Upper	0.02	0.66	0.03	23.11	1.67	0.10	16.33
Churchill	BrU6	Upper	0.04	1.55	0.06	25.92	2.89	0.10	28.04
Churchill	BrU7	Upper	0.02	0.91	0.04	24.76	2.64	0.10	26.00
Churchill	BrU8	Upper	0.02	0.87	0.04	20.56	2.34	0.12	19.28
Churchill	BrU9	Upper	0.04	1.69	0.08	21.21	2.87	0.16	18.24
Churchill	BrU10	Upper	0.04	1.60	0.07	22.34	2.21	0.11	20.49
Churchill	BrU11	Upper	0.05	2.23	0.10	22.85	3.65	0.15	23.61
Churchill	BrU12	Upper	0.05	2.02	0.09	23.02	2.73	0.16	17.59
Churchill	BrB1	Back	0.03	1.23	0.04	31.05	3.12	0.16	19.51
Churchill	BrB2	Back	0.05	2.29	0.07	30.89	3.51	0.16	21.86
Churchill	BrB3	Back	0.06	2.57	0.08	34.09	3.89	0.18	22.01
Churchill	BrB4	Back	0.05	2.21	0.10	21.22	3.75	0.20	19.11

Ecosystem	Point	Topo	LF Qty	C-LF	N-LF	LF C:N	C-HF	N-HF	HF C:N
			g g^{-1}	g $100g^{-1}$	g $100g^{-1}$		g $100g^{-1}$	g $100g^{-1}$	
Churchill	BrB5	Back	0.07	2.98	0.10	28.77	3.72	0.18	20.86
Churchill	BrB6	Back	0.05	1.87	0.05	36.05	3.95	0.17	23.12
Churchill	BrB7	Back	0.02	0.92	0.04	24.56	2.19	0.14	15.45
Churchill	BrB8	Back	0.05	1.91	0.06	33.55	3.60	0.18	20.29
Churchill	BrB9	Back	0.04	1.52	0.04	37.55	4.26	0.21	20.59
Churchill	BrB10	Back	0.03	1.07	0.03	33.67	2.64	0.15	17.37
Churchill	BrB11	Back	0.03	1.21	0.04	31.26	4.35	0.22	19.54
Churchill	BrB12	Back	0.02	0.75	0.02	35.09	6.48	0.27	23.87
Churchill	BrL1	Lower	0.24	9.90	0.36	27.68	18.37	0.85	21.68
Churchill	BrL2	Lower	0.13	5.14	0.20	25.60	25.41	0.71	35.68
Churchill	BrL3	Lower	0.26	10.69	0.46	23.31	15.19	0.94	16.20
Churchill	BrL4	Lower	0.09	3.65	0.11	32.62	12.84	0.40	32.36
Churchill	BrL5	Lower	0.12	4.60	0.20	22.46	19.42	1.11	17.51
Churchill	BrL6	Lower	0.07	2.83	0.14	19.66	10.08	0.43	23.62
Churchill	BrL7	Lower	0.04	1.69	0.06	28.21	10.14	0.47	21.57
Churchill	BrL8	Lower	0.06	2.70	0.12	23.26	10.21	0.46	22.04
Churchill	BrL9	Lower	0.16	6.67	0.38	17.33	7.16	0.46	15.53
Churchill	BrL10	Lower	0.14	5.80	0.17	34.79	9.80	0.61	15.94
Churchill	BrL11	Lower	0.12	4.79	0.15	32.36	9.63	0.45	21.46
Churchill	BrL12	Lower	0.07	2.66	0.09	28.86	8.34	0.44	18.79
Churchill	HW1	Wedge	0.64	29.41	1.83	16.11	15.35	1.19	12.90
Churchill	HW2	Wedge	0.34	14.70	0.89	16.55	13.13	1.23	10.70
Churchill	HW3	Wedge	0.57	25.28	1.50	16.83	18.54	1.43	12.92
Churchill	HW4	Wedge	0.34	14.45	0.73	19.91	17.62	1.21	14.57
Churchill	HW5	Wedge	0.48	20.96	1.38	15.17	16.77	1.38	12.15
Churchill	HW6	Wedge	0.54	24.14	1.71	14.10	19.73	1.50	13.12
Churchill	HW7	Wedge	0.64	28.48	1.72	16.53	14.69	1.09	13.44
Churchill	HW8	Wedge	0.67	29.62	2.17	13.65	13.10	1.11	11.80
Churchill	HW9	Wedge	0.59	26.19	1.76	14.85	17.07	1.44	11.82
Churchill	HW10	Wedge	0.43	19.12	1.24	15.45	22.77	1.78	12.76
Churchill	HW11	Wedge	0.62	27.67	1.92	14.41	15.29	1.19	12.86
Churchill	HW12	Wedge	0.32	13.74	0.70	19.68	17.31	1.10	15.79
Churchill	HW13	Wedge	0.27	11.55	0.53	21.91	9.31	0.46	20.19
Churchill	HW14	Wedge	0.29	12.28	0.70	17.45	20.69	1.34	15.41
Churchill	HW15	Wedge	0.36	15.46	1.05	14.78	25.74	1.99	12.96
Churchill	HP1	Hummock	0.82	37.50	0.87	43.30	7.90	0.26	30.21
Churchill	HP2	Hummock	0.79	36.15	1.04	34.85	9.01	0.44	20.32
Churchill	HP3	Hummock	0.87	40.87	0.97	42.34	5.44	0.20	26.74
Churchill	HP4	Hummock	0.53	24.30	0.78	31.09	18.57	0.90	20.65
Churchill	HP5	Hummock	0.61	27.91	1.19	23.49	16.99	1.08	15.70
Churchill	HP6	Hummock	0.77	35.97	0.81	44.25	10.22	0.29	35.66
Churchill	HP7	Hummock	0.78	37.05	0.73	50.64	9.60	0.23	40.87
Churchill	HP8	Hummock	0.71	32.21	0.45	71.75	12.68	0.23	56.10
Churchill	HP9	Hummock	0.80	38.12	0.83	45.87	8.82	0.20	43.06
Churchill	HP10	Hummock	0.58	26.02	1.08	24.11	17.76	1.05	16.85

Ecosystem	Point	Topo	LF Qty	C-LF	N-LF	LF C:N	C-HF	N-HF	HF C:N
			g g^{-1}	g $100g^{-1}$	g $100g^{-1}$		g $100g^{-1}$	g $100g^{-1}$	
Churchill	HP11	Hummock	0.59	25.73	0.85	30.28	17.28	0.93	18.50
Churchill	HP12	Hummock	0.57	25.56	0.88	29.03	16.75	0.79	21.26
Churchill	HP13	Hummock	0.87	41.34	1.11	37.27	5.97	0.17	34.45
Churchill	HP14	Hummock	0.72	33.26	0.88	37.93	11.83	0.44	27.03
Churchill	HP15	Hummock	0.73	31.97	1.07	29.80	10.45	0.62	16.89
Daring Lake	Ua15	Up	0.01	0.42	0.02	26.33	3.86	0.26	15.42
Daring Lake	Ua10	Up	0.01	0.31	0.01	25.00	7.08	0.39	18.16
Daring Lake	Ua5	Up	0.01	0.20	0.01	28.81	3.97	0.24	15.57
Daring Lake	Ua0	Up	0.01	0.58	0.02	33.09	2.79	0.19	15.21
Daring Lake	Ba15	Back	0.01	0.38	0.01	34.30	2.94	0.12	24.25
Daring Lake	Ba10	Back	0.15	6.59	0.21	31.27	5.89	0.26	23.41
Daring Lake	Ba5	Back	0.01	0.30	0.01	33.45	2.20	0.08	24.94
Daring Lake	Ba0	Back	0.02	0.74	0.02	32.31	2.90	0.14	23.29
Daring Lake	La15	Low	0.03	1.23	0.04	28.05	9.73	0.47	22.06
Daring Lake	La10	Low	0.70	31.11	1.12	27.88	11.75	0.45	26.01
Daring Lake	La5	Low	0.01	0.29	0.01	38.39	3.93	0.15	25.76
Daring Lake	La0	Low	0.50	21.46	0.67	32.18	15.20	0.53	30.66
Daring Lake	Ub15	Up	0.01	0.57	0.02	27.70	3.95	0.20	18.33
Daring Lake	Ub10	Up	0.05	1.99	0.07	26.98	6.03	0.34	19.66
Daring Lake	Ub5	Up	0.01	0.62	0.02	27.87	4.02	0.24	15.83
Daring Lake	Ub0	Up	0.01	0.40	0.01	31.59	3.36	0.18	16.61
Daring Lake	Bb15	Back	0.27	11.37	0.40	28.53	12.12	0.46	24.60
Daring Lake	Bb10	Back	0.09	4.21	0.16	25.67	7.09	0.32	21.55
Daring Lake	Bb5	Back	0.01	0.21	0.01	40.36	1.71	0.06	25.76
Daring Lake	Bb0	Back	0.01	0.22	0.01	33.36	1.91	0.08	24.53
Daring Lake	Lb15	Low	0.01	0.34	0.01	40.78	3.00	0.12	26.05
Daring Lake	Lb10	Low	0.10	4.32	0.12	36.47	11.75	0.40	28.76
Daring Lake	Lb5	Low	0.01	0.41	0.01	52.94	2.26	0.09	25.59
Daring Lake	Lb0	Low	0.66	29.51	0.80	36.89	13.44	0.42	31.82
Daring Lake	Uc15	Up	0.03	1.10	0.04	27.53	5.25	0.29	18.15
Daring Lake	Uc10	Up	0.01	0.59	0.02	30.53	6.36	0.38	16.12
Daring Lake	Uc5	Up	0.04	2.01	0.08	26.61	11.67	0.65	19.35
Daring Lake	Uc0	Up	0.02	0.71	0.03	27.62	3.17	0.16	19.07
Daring Lake	Bc15	Back	0.02	0.63	0.02	26.69	2.47	0.11	21.30
Daring Lake	Bc10	Back	0.06	2.27	0.07	31.10	6.09	0.24	24.98
Daring Lake	Bc5	Back	0.00	-0.09	0.00	26.90	1.88	0.13	18.45
Daring Lake	Bc0	Back	0.00	0.15	0.00	40.24	1.61	0.06	25.04
Daring Lake	Lc15	Low	0.00	0.00	0.00	40.85	1.27	0.05	24.56
Daring Lake	Lc10	Low	0.00	0.00	0.00	42.39	3.93	0.15	28.07
Daring Lake	Lc5	Low	0.77	32.72	0.95	34.44	9.01	0.27	33.45
Daring Lake	Lc0	Low	0.76	34.75	0.98	35.31	8.49	0.23	32.99
Daring Lake	Ud15	Up	0.03	1.18	0.04	27.42	4.69	0.27	17.34
Daring Lake	Ud10	Up	0.01	0.40	0.02	25.14	4.97	0.32	15.99
Daring Lake	Ud5	Up	0.01	0.23	0.01	26.10	4.31	0.27	16.57
Daring Lake	Ud0	Up	0.00	0.14	0.01	25.64	3.65	0.25	15.44

Ecosystem	Point	Topo	LF Qty	C-LF	N-LF	LF C:N	C-HF	N-HF	HF C:N
			g g^{-1}	g $100g^{-1}$	g $100g^{-1}$		g $100g^{-1}$	g $100g^{-1}$	
Daring Lake	Bd15	Back	0.02	0.83	0.03	30.69	5.96	0.26	25.63
Daring Lake	Bd10	Back	0.48	20.76	0.92	22.55	11.95	0.61	21.10
Daring Lake	Bd5	Back	0.01	0.20	0.01	26.80	3.01	0.16	22.42
Daring Lake	Bd0	Back	0.01	0.36	0.01	38.30	2.59	0.09	28.28
Daring Lake	Ld15	Low	0.87	39.86	1.37	29.11	4.10	0.15	26.67
Daring Lake	Ld10	Low	0.90	33.36	1.01	32.92	3.64	0.11	32.16
Daring Lake	Ld5	Low	0.75	34.22	1.17	29.35	8.00	0.32	25.39
Daring Lake	Ld0	Low	0.81	36.50	1.09	33.43	6.96	0.24	28.68
Daring Lake	Ue15	Up	0.01	0.45	0.02	28.82	4.21	0.31	14.47
Daring Lake	Ue10	Up	0.01	0.53	0.02	30.25	7.23	0.41	17.86
Daring Lake	Ue5	Up	0.01	0.23	0.01	26.15	3.86	0.23	16.18
Daring Lake	Ue0	Up	0.01	0.24	0.01	25.44	2.90	0.17	15.35
Daring Lake	Be15	Back	0.06	2.58	0.09	27.38	3.83	0.16	24.39
Daring Lake	Be10	Back	0.02	0.58	0.02	37.31	2.38	0.08	30.37
Daring Lake	Be5	Back	0.01	0.34	0.01	26.25	4.09	0.23	20.81
Daring Lake	Be0	Back	0.04	1.52	0.04	35.66	2.92	0.11	28.07
Daring Lake	Le15	Low	0.62	28.84	1.02	28.17	9.87	0.41	24.82
Daring Lake	Le10	Low	0.07	3.00	0.09	32.33	10.65	0.41	26.36
Daring Lake	Le5	Low	0.78	35.98	1.07	33.48	7.94	0.26	30.43
Daring Lake	Le0	Low	0.00	-0.09	0.00	40.37	2.45	0.09	27.00
Truelove	TU1	Up	0.12	5.09	0.27	18.81	16.61	1.12	14.81
Truelove	TU2	Up	0.13	5.23	0.30	17.63	17.97	1.27	14.17
Truelove	TU3	Up	0.19	8.07	0.41	19.76	14.62	1.06	13.85
Truelove	TU4	Up	0.12	4.94	0.26	18.65	23.64	1.65	14.34
Truelove	TU5	Up	0.09	3.78	0.20	18.73	26.00	1.85	14.02
Truelove	TU6	Up	0.34	14.76	0.72	20.42	17.97	1.23	14.66
Truelove	TU7	Up	0.17	6.82	0.33	20.56	18.49	1.40	13.22
Truelove	TU8	Up	0.05	2.03	0.10	19.54	13.55	0.89	15.16
Truelove	TU9	Up	0.19	7.60	0.38	19.95	15.29	1.05	14.58
Truelove	TU10	Up	0.11	3.97	0.20	19.73	16.21	1.10	14.76
Truelove	TB1	Back	0.05	1.98	0.11	17.31	26.01	2.01	12.92
Truelove	TB2	Back	0.04	1.38	0.08	16.88	20.14	1.48	13.57
Truelove	TB3	Back	0.06	2.11	0.12	17.35	22.82	1.66	13.76
Truelove	TB4	Back	0.03	1.14	0.07	17.30	19.66	1.61	12.18
Truelove	TB5	Back	0.03	0.85	0.05	17.91	20.96	1.62	12.96
Truelove	TB6	Back	0.05	1.70	0.10	16.85	26.04	1.82	14.30
Truelove	TB7	Back	0.04	1.12	0.07	15.98	21.27	1.89	11.27
Truelove	TB8	Back	0.13	4.95	0.28	17.66	22.49	1.69	13.34
Truelove	TB9	Back	0.10	3.60	0.19	19.17	23.27	1.66	14.03
Truelove	TB10	Back	0.05	1.73	0.11	16.44	24.51	1.90	12.90
Truelove	TL1	Low	0.01	0.29	0.02	18.09	25.97	2.14	12.14
Truelove	TL2	Low	0.01	0.29	0.02	18.90	14.75	1.15	12.84
Truelove	TL3	Low	0.01	0.26	0.01	22.24	16.24	1.22	13.33
Truelove	TL4	Low	0.01	0.23	0.01	30.05	3.59	0.16	22.94
Truelove	TL5	Low	0.01	0.23	0.01	25.91	12.81	0.97	13.16

Ecosystem	Point	Topo	LF Qty	C-LF	N-LF	LF C:N	C-HF	N-HF	HF C:N
			g g^{-1}	g $100g^{-1}$	g $100g^{-1}$		g $100g^{-1}$	g $100g^{-1}$	
Truelove	TL6	Low	0.01	0.22	0.01	23.74	8.60	0.57	15.06
Truelove	TL7	Low	0.05	1.50	0.09	16.76	22.80	1.54	14.80
Truelove	TL8	Low	0.01	0.29	0.01	30.27	21.63	1.63	13.24
Truelove	TL9	Low	0.12	3.24	0.15	21.17	24.97	1.36	18.42
Truelove	TL10	Low	0.36	13.46	0.82	16.39	22.36	1.53	14.66
Truelove	W1.1	Wedge	0.14	4.90	0.27	18.08	26.03	1.79	14.57
Truelove	W1.2	Wedge	0.10	3.85	0.19	20.00	26.45	1.82	14.56
Truelove	W2.1	Wedge	0.31	10.96	0.58	18.88	23.02	1.50	15.35
Truelove	W2.2	Wedge	0.34	9.42	0.55	17.25	16.52	1.16	14.25
Truelove	W3	Wedge	0.03	1.05	0.06	16.37	24.54	1.93	12.70
Truelove	W4	Wedge	0.66	29.02	1.28	22.75	12.72	0.70	18.12
Truelove	W5	Wedge	0.01	0.25	0.02	16.10	22.88	1.75	13.06
Truelove	W6	Wedge	0.50	20.73	0.99	20.90	19.03	1.09	17.39
Truelove	W7	Wedge	0.12	4.19	0.23	18.02	24.67	1.62	15.26
Truelove	W8	Wedge	0.14	5.21	0.29	18.09	23.18	1.64	14.13
Truelove	W9	Wedge	0.01	0.28	0.01	23.50	23.93	1.57	15.20
Truelove	W10	Wedge	0.56	23.11	0.92	25.15	17.73	0.79	22.57
Truelove	P1.1	Hummock	0.14	5.40	0.32	16.87	23.92	1.80	13.29
Truelove	P1.2	Hummock	0.18	7.22	0.40	18.19	23.42	1.76	13.28
Truelove	P2.1	Hummock	0.20	7.90	0.48	16.30	22.34	1.70	13.11
Truelove	P2.2	Hummock	0.25	9.97	0.58	17.09	21.42	1.61	13.28
Truelove	P3	Hummock	0.23	9.22	0.56	16.58	21.09	1.62	13.00
Truelove	P4	Hummock	0.19	7.55	0.41	18.36	23.62	1.69	13.98
Truelove	P5	Hummock	0.17	7.00	0.41	17.05	22.94	1.82	12.63
Truelove	P6	Hummock	0.11	4.22	0.23	18.55	23.80	1.80	13.25
Truelove	P7	Hummock	0.10	3.83	0.21	18.65	24.84	1.80	13.77
Truelove	P8	Hummock	0.09	3.33	0.19	17.98	25.72	1.91	13.45
Truelove	P9	Hummock	0.07	2.39	0.15	16.41	25.44	1.94	13.14
Truelove	P10	Hummock	0.17	6.67	0.40	16.75	23.63	1.84	12.82

Table F 5: Solid-State ^{13}C NMR.

Ecosystem	Point	Topo	AC	OAC	CC	MC	AroC	CbyC	OAC : AroC	OAC : AC
			%	%	%	%	%	%		
Churchill	DU1	Upper	22.29	56.71	38.35	9.99	12.53	8.47	4.53	2.54
Churchill	DU2	Upper	24.13	53.70	36.21	9.72	12.64	9.53	4.25	2.23
Churchill	DU3	Upper	20.18	58.09	42.95	7.14	12.98	8.74	4.47	2.88
Churchill	DU4	Upper	19.98	51.80	34.69	8.50	16.45	11.77	3.15	2.59
Churchill	DU5	Upper	21.37	53.67	36.91	8.48	14.37	10.58	3.73	2.51
Churchill	DU6	Upper	23.02	55.29	37.80	9.21	13.71	7.97	4.03	2.40
Churchill	DU7	Upper	24.06	58.70	42.20	9.14	9.13	8.12	6.43	2.44
Churchill	DU8	Upper	23.68	56.00	40.07	8.60	9.74	10.58	5.75	2.36
Churchill	DU9	Upper	24.72	55.59	39.39	9.46	9.44	10.25	5.89	2.25
Churchill	DU10	Upper	20.51	55.89	38.46	8.73	12.47	11.14	4.48	2.73
Churchill	DU11	Upper	21.72	56.53	39.73	8.78	11.44	10.31	4.94	2.60
Churchill	DU12	Upper	20.99	61.34	43.37	8.99	10.62	7.05	5.77	2.92
Churchill	DB1	Back	17.85	58.46	39.37	8.45	15.65	8.03	3.73	3.27
Churchill	DB2	Back	17.92	69.39	51.46	6.76	7.66	5.03	9.05	3.87
Churchill	DB3	Back	19.98	63.48	46.05	7.49	9.19	7.35	6.90	3.18
Churchill	DB4	Back	19.50	63.49	45.75	7.81	10.12	6.90	6.28	3.26
Churchill	DB5	Back	20.85	63.02	46.20	7.09	8.47	7.66	7.44	3.02
Churchill	DB6	Back	18.73	62.38	44.72	7.80	10.58	8.30	5.90	3.33
Churchill	DB7	Back	19.06	62.35	45.54	6.68	10.28	8.31	6.07	3.27
Churchill	DB8	Back	21.87	59.74	42.82	7.94	9.00	9.39	6.63	2.73
Churchill	DB9	Back	22.73	61.19	43.86	8.64	7.67	8.41	7.98	2.69
Churchill	DB10	Back	18.09	63.48	44.66	8.97	11.64	6.79	5.46	3.51
Churchill	DB11	Back	20.39	61.85	44.68	7.20	9.91	7.84	6.24	3.03
Churchill	DB12	Back	20.36	63.52	45.85	7.71	9.15	6.97	6.94	3.12
Churchill	DL1	Lower	18.32	65.38	47.80	7.10	9.41	6.88	6.95	3.57
Churchill	DL2	Lower	19.79	65.87	49.97	5.35	7.06	7.29	9.33	3.33
Churchill	DL3	Lower	20.89	61.04	44.05	7.34	9.34	8.73	6.54	2.92
Churchill	DL4	Lower	22.58	62.32	44.75	8.16	8.03	7.07	7.76	2.76
Churchill	DL5	Lower	20.66	61.49	42.96	8.67	10.78	7.06	5.70	2.98
Churchill	DL6	Lower	21.54	62.94	46.09	6.86	8.95	6.58	7.03	2.92
Churchill	DL7	Lower	21.60	61.94	44.96	7.50	9.29	7.16	6.67	2.87
Churchill	DL8	Lower	20.28	62.78	44.99	7.40	10.13	6.80	6.19	3.09
Churchill	DL9	Lower	21.46	60.92	42.85	8.18	10.43	7.19	5.84	2.84
Churchill	DL10	Lower	20.91	63.73	46.08	7.83	8.97	6.39	7.10	3.05
Churchill	DL11	Lower	19.17	63.87	46.73	5.99	9.95	7.01	6.42	3.33
Churchill	DL12	Lower	22.19	61.85	43.94	7.84	9.91	6.04	6.24	2.79
Churchill	BgU1	Upper	19.17	56.27	38.14	8.85	15.45	9.12	3.64	2.94
Churchill	BgU2	Upper	20.09	57.69	38.29	10.38	15.24	6.97	3.78	2.87
Churchill	BgU3	Upper	23.86	54.38	41.73	7.63	16.79	4.98	3.24	2.28
Churchill	BgU4	Upper	28.24	51.65	35.78	11.27	12.56	7.54	4.11	1.83
Churchill	BgU5	Upper	18.79	58.21	42.16	7.64	12.17	10.82	4.78	3.10
Churchill	BgU6	Upper	16.01	54.71	39.64	6.87	15.78	13.50	3.47	3.42
Churchill	BgU7	Upper	21.93	50.13	32.11	9.93	19.98	7.96	2.51	2.29

Ecosystem	Point	Topo	AC	OAC	CC	MC	AroC	CbyC	OAC : AroC	OAC : AC
			%	%	%	%	%	%		
Churchill	BgU8	Upper	15.87	47.52	33.49	6.70	22.20	14.42	2.14	2.99
Churchill	BgU9	Upper	12.88	55.01	39.29	6.55	16.07	16.04	3.42	4.27
Churchill	BgU10	Upper	17.23	47.15	33.00	6.79	20.11	15.50	2.34	2.74
Churchill	BgU11	Upper	23.02	53.34	37.87	8.33	12.31	11.33	4.33	2.32
Churchill	BgU12	Upper								
Churchill	BgB1	Back	20.38	61.44	43.76	9.17	9.83	8.34	6.25	3.01
Churchill	BgB2	Back	19.15	62.84	46.16	7.07	9.51	8.50	6.61	3.28
Churchill	BgB3	Back	18.16	64.63	46.61	8.27	9.49	7.72	6.81	3.56
Churchill	BgB4	Back	17.66	57.52	40.41	7.08	14.28	10.54	4.03	3.26
Churchill	BgB5	Back	21.32	59.30	41.89	8.37	10.82	8.56	5.48	2.78
Churchill	BgB6	Back	17.54	64.58	48.01	5.70	9.20	8.68	7.02	3.68
Churchill	BgB7	Back	14.39	70.50	53.16	4.98	8.35	6.75	8.44	4.90
Churchill	BgB8	Back	17.72	65.24	47.03	7.27	10.16	6.88	6.42	3.68
Churchill	BgB9	Back	17.59	62.57	43.76	8.46	11.88	7.96	5.26	3.56
Churchill	BgB10	Back	18.69	65.04	46.12	8.91	9.80	6.47	6.64	3.48
Churchill	BgB11	Back	19.39	67.59	49.89	7.45	8.02	5.00	8.42	3.49
Churchill	BgB12	Back	20.74	61.46	43.74	8.88	9.40	8.40	6.54	2.96
Churchill	BgL1	Lower	14.58	71.06	50.70	11.03	8.60	5.76	8.27	4.87
Churchill	BgL2	Lower	19.26	66.74	49.04	7.73	7.53	6.47	8.87	3.46
Churchill	BgL3	Lower	17.97	66.54	48.45	8.35	7.95	7.54	8.37	3.70
Churchill	BgL4	Lower	16.70	66.70	48.41	8.12	8.74	7.86	7.63	3.99
Churchill	BgL5	Lower	18.10	65.09	47.19	8.32	8.70	8.11	7.48	3.60
Churchill	BgL6	Lower	18.22	66.17	48.30	7.92	8.58	7.03	7.71	3.63
Churchill	BgL7	Lower	19.24	63.39	45.58	8.52	8.84	8.53	7.17	3.29
Churchill	BgL8	Lower	19.16	66.18	48.29	7.87	7.46	7.19	8.87	3.45
Churchill	BgL9	Lower	18.21	65.53	47.19	7.81	9.61	6.64	6.82	3.60
Churchill	BgL10	Lower	19.77	64.19	46.00	8.62	8.63	7.41	7.44	3.25
Churchill	BgL11	Lower	16.33	64.95	47.10	7.90	10.32	8.40	6.30	3.98
Churchill	BgL12	Lower	16.39	68.29	50.05	7.39	9.00	6.33	7.59	4.17
Churchill	BrU1	Upper	21.91	51.61	36.47	7.86	15.71	10.77	3.28	2.36
Churchill	BrU2	Upper	21.08	54.69	39.42	7.62	14.05	10.18	3.89	2.59
Churchill	BrU3	Upper	17.81	52.26	36.68	7.37	17.49	12.45	2.99	2.93
Churchill	BrU4	Upper	19.41	57.67	39.50	10.04	14.51	8.41	3.97	2.97
Churchill	BrU5	Upper	18.42	57.42	39.44	9.02	17.70	6.46	3.24	3.12
Churchill	BrU6	Upper	20.76	59.03	41.51	9.50	12.73	7.48	4.64	2.84
Churchill	BrU7	Upper	18.78	54.01	39.51	6.91	16.23	10.98	3.33	2.88
Churchill	BrU8	Upper	19.62	57.24	40.04	8.70	14.32	8.82	4.00	2.92
Churchill	BrU9	Upper	20.74	56.46	42.38	6.78	10.44	12.35	5.41	2.72
Churchill	BrU10	Upper	23.80	57.26	41.59	7.40	9.59	9.35	5.97	2.41
Churchill	BrU11	Upper	22.48	61.86	44.40	8.89	9.22	6.44	6.71	2.75
Churchill	BrU12	Upper	19.27	58.11	40.62	8.72	14.93	7.69	3.89	3.01
Churchill	BrB1	Back	14.70	59.90	45.44	4.61	12.65	12.75	4.74	4.07
Churchill	BrB2	Back	18.61	63.51	49.10	6.00	6.57	11.31	9.66	3.41
Churchill	BrB3	Back	19.57	64.03	48.47	7.06	7.49	8.90	8.54	3.27
Churchill	BrB4	Back	20.10	63.92	50.22	6.11	6.53	9.45	9.79	3.18

Ecosystem	Point	Topo	AC	OAC	CC	MC	AroC	CbyC	OAC : AroC	OAC : AC
			%	%	%	%	%	%		
Churchill	BrB5	Back	19.88	65.54	51.09	6.53	4.17	10.41	15.73	3.30
Churchill	BrB6	Back	19.35	60.23	46.78	5.97	7.07	13.35	8.52	3.11
Churchill	BrB7	Back	13.68	56.14	42.50	4.47	15.18	15.00	3.70	4.10
Churchill	BrB8	Back	19.04	60.52	44.91	8.02	10.95	9.49	5.53	3.18
Churchill	BrB9	Back	18.62	70.33	54.41	7.30	4.68	6.37	15.01	3.78
Churchill	BrB10	Back	16.44	62.38	46.46	6.82	10.43	10.75	5.98	3.80
Churchill	BrB11	Back	20.25	59.67	45.62	7.55	8.95	11.14	6.67	2.95
Churchill	BrB12	Back	21.43	67.28	49.85	9.22	4.94	6.35	13.63	3.14
Churchill	BrL1	Lower	17.64	63.99	45.65	7.84	10.70	7.67	5.98	3.63
Churchill	BrL2	Lower	18.16	65.07	47.51	7.68	8.83	7.95	7.37	3.58
Churchill	BrL3	Lower	18.54	66.22	47.30	8.66	9.24	6.00	7.17	3.57
Churchill	BrL4	Lower	17.46	63.90	45.41	8.26	11.02	7.62	5.80	3.66
Churchill	BrL5	Lower	21.77	63.76	46.85	8.84	6.81	7.66	9.36	2.93
Churchill	BrL6	Lower	20.62	63.16	44.98	9.47	8.76	7.46	7.21	3.06
Churchill	BrL7	Lower	19.30	64.91	47.58	8.76	7.99	7.80	8.13	3.36
Churchill	BrL8	Lower	20.74	62.10	44.40	8.75	8.71	8.44	7.13	2.99
Churchill	BrL9	Lower	21.28	62.87	45.24	8.89	8.26	7.59	7.61	2.95
Churchill	BrL10	Lower	18.88	66.70	48.50	8.18	8.58	5.84	7.77	3.53
Churchill	BrL11	Lower	19.39	64.36	46.38	8.71	8.28	7.98	7.77	3.32
Churchill	BrL12	Lower	19.52	62.90	45.11	8.69	9.58	8.00	6.56	3.22
Churchill	HW1	Wedge	19.05	65.30	47.55	7.37	8.61	7.04	7.58	3.43
Churchill	HW2	Wedge	21.67	65.84	47.84	8.55	6.16	6.33	10.69	3.04
Churchill	HW3	Wedge	19.11	65.18	47.75	7.64	7.81	7.90	8.35	3.41
Churchill	HW4	Wedge	21.30	65.02	47.42	8.24	6.84	6.84	9.51	3.05
Churchill	HW5	Wedge	21.63	64.47	47.02	8.04	6.71	7.19	9.61	2.98
Churchill	HW6	Wedge	19.71	63.75	45.96	7.81	8.66	7.88	7.36	3.23
Churchill	HW7	Wedge	19.69	65.25	46.94	8.41	8.55	6.51	7.63	3.31
Churchill	HW8	Wedge	19.83	64.46	46.71	7.99	8.06	7.65	8.00	3.25
Churchill	HW9	Wedge	19.21	64.98	47.25	7.97	7.85	7.96	8.27	3.38
Churchill	HW10	Wedge	19.84	64.54	46.37	8.40	8.12	7.50	7.95	3.25
Churchill	HW11	Wedge	21.08	64.16	46.41	8.06	7.81	6.94	8.22	3.04
Churchill	HW12	Wedge	21.18	63.58	46.40	7.44	7.86	7.38	8.09	3.00
Churchill	HW13	Wedge	24.78	65.77	48.40	7.78	5.31	4.15	12.38	2.65
Churchill	HW14	Wedge	20.03	63.80	45.92	8.81	7.97	8.21	8.01	3.19
Churchill	HW15	Wedge	20.42	63.84	45.47	8.93	8.19	7.55	7.79	3.13
Churchill	HP1	Hummock	19.10	66.95	49.46	7.37	7.40	6.55	9.04	3.50
Churchill	HP2	Hummock	19.48	68.11	51.26	5.66	7.44	4.97	9.16	3.50
Churchill	HP3	Hummock	19.03	64.88	47.75	6.18	9.92	6.17	6.54	3.41
Churchill	HP4	Hummock	18.40	67.22	49.84	6.46	8.41	5.96	7.99	3.65
Churchill	HP5	Hummock	17.28	68.01	50.73	6.28	8.21	6.49	8.28	3.94
Churchill	HP6	Hummock	18.22	70.19	53.61	5.14	6.71	4.88	10.46	3.85
Churchill	HP7	Hummock	18.47	71.08	54.40	5.37	6.05	4.40	11.75	3.85
Churchill	HP8	Hummock	14.68	75.30	57.65	5.50	5.25	4.76	14.33	5.13
Churchill	HP9	Hummock	18.55	69.95	52.59	5.74	7.42	4.08	9.43	3.77
Churchill	HP10	Hummock	18.57	66.27	48.08	7.49	8.96	6.21	7.39	3.57

Ecosystem	Point	Topo	AC	OAC	CC	MC	AroC	CbyC	OAC : AroC	OAC : AC
			%	%	%	%	%	%		
Churchill	HP11	Hummock	18.35	68.85	50.92	7.16	7.45	5.34	9.24	3.75
Churchill	HP12	Hummock	19.79	66.34	49.50	6.42	7.71	6.16	8.60	3.35
Churchill	HP13	Hummock	18.76	67.95	51.21	5.38	8.11	5.18	8.38	3.62
Churchill	HP14	Hummock	19.81	68.94	51.86	5.82	6.97	4.28	9.88	3.48
Churchill	HP15	Hummock	17.90	68.51	52.07	5.21	7.69	5.90	8.90	3.83
Daring Lake	Ua15	Up	28.43	44.25	31.11	6.94	14.39	12.93	3.08	1.56
Daring Lake	Ua10	Up	34.72	46.31	31.60	8.36	11.46	7.52	4.04	1.33
Daring Lake	Ua5	Up	28.68	37.75	22.98	8.06	21.06	12.51	1.79	1.32
Daring Lake	Ua0	Up	19.51	39.96	29.78	4.52	19.16	21.37	2.09	2.05
Daring Lake	Ba15	Back	28.41	42.61	29.75	5.45	15.28	13.69	2.79	1.50
Daring Lake	Ba10	Back	25.96	61.27	41.22	11.00	10.20	2.57	6.01	2.36
Daring Lake	Ba5	Back	23.84	41.09	28.66	5.82	21.04	14.04	1.95	1.72
Daring Lake	Ba0	Back	27.30	50.60	34.32	7.80	16.20	5.90	3.12	1.85
Daring Lake	La15	Low	25.36	58.36	40.49	8.60	12.36	3.91	4.72	2.30
Daring Lake	La10	Low	22.95	63.16	45.44	7.52	8.90	4.99	7.09	2.75
Daring Lake	La5	Low	27.13	56.93	40.19	8.65	10.13	5.81	5.62	2.10
Daring Lake	La0	Low	23.72	61.80	45.24	6.33	9.05	5.42	6.83	2.61
Daring Lake	Ub15	Up	21.14	46.22	30.74	6.96	19.83	12.82	2.33	2.19
Daring Lake	Ub10	Up	25.40	52.75	36.86	7.87	12.26	9.60	4.30	2.08
Daring Lake	Ub5	Up	18.53	33.94	22.89	5.79	20.00	27.52	1.70	1.83
Daring Lake	Ub0	Up								
Daring Lake	Bb15	Back	27.49	60.82	44.27	7.49	7.19	4.50	8.46	2.21
Daring Lake	Bb10	Back	24.80	51.76	34.39	8.39	15.08	8.37	3.43	2.09
Daring Lake	Bb5	Back	20.89	50.82	32.72	9.25	21.02	7.27	2.42	2.43
Daring Lake	Bb0	Back	27.14	48.39	30.83	8.73	19.34	5.13	2.50	1.78
Daring Lake	Lb15	Low	18.49	58.09	39.77	8.74	19.40	4.01	2.99	3.14
Daring Lake	Lb10	Low	26.20	59.73	42.22	8.00	9.91	4.17	6.03	2.28
Daring Lake	Lb5	Low	25.02	46.24	35.43	5.56	13.21	15.53	3.50	1.85
Daring Lake	Lb0	Low	19.63	68.24	52.16	4.57	7.50	4.63	9.10	3.48
Daring Lake	Uc15	Up	25.74	55.28	36.57	9.87	13.28	5.69	4.16	2.15
Daring Lake	Uc10	Up	31.54	45.92	32.88	6.31	11.11	11.43	4.13	1.46
Daring Lake	Uc5	Up	29.65	51.28	34.59	9.28	10.31	8.76	4.97	1.73
Daring Lake	Uc0	Up								
Daring Lake	Bc15	Back	25.91	40.82	27.22	6.95	19.30	13.97	2.11	1.58
Daring Lake	Bc10	Back	32.69	54.45	39.05	8.63	7.58	5.28	7.18	1.67
Daring Lake	Bc5	Back	17.68	39.95	24.33	6.72	28.31	14.07	1.41	2.26
Daring Lake	Bc0	Back	26.09	41.71	30.95	3.69	15.28	16.92	2.73	1.60
Daring Lake	Lc15	Low								
Daring Lake	Lc10	Low	30.03	49.71	35.69	6.45	10.56	9.71	4.71	1.66
Daring Lake	Lc5	Low	19.91	66.85	48.57	7.09	9.03	4.21	7.40	3.36
Daring Lake	Lc0	Low	20.73	70.18	52.48	6.56	6.36	2.73	11.03	3.39
Daring Lake	Ud15	Up	29.81	46.49	30.16	9.29	16.06	7.64	2.89	1.56
Daring Lake	Ud10	Up	33.31	41.20	30.61	5.28	10.31	15.19	3.99	1.24
Daring Lake	Ud5	Up	20.48	30.67	19.89	5.26	18.80	30.06	1.63	1.50
Daring Lake	Ud0	Up								

Ecosystem	Point	Topo	AC	OAC	CC	MC	AroC	CbyC	OAC : AroC	OAC : AC
			%	%	%	%	%	%		
Daring Lake	Bd15	Back	22.33	60.00	42.48	7.84	11.38	6.28	5.27	2.69
Daring Lake	Bd10	Back	31.04	57.61	41.91	7.85	5.34	6.01	10.79	1.86
Daring Lake	Bd5	Back	18.97	54.83	36.58	8.01	21.22	4.97	2.58	2.89
Daring Lake	Bd0	Back	26.17	44.16	29.38	7.21	19.15	10.52	2.31	1.69
Daring Lake	Ld15	Low	23.85	63.92	46.99	6.68	7.62	4.61	8.39	2.68
Daring Lake	Ld10	Low	21.72	71.56	55.14	5.51	3.63	3.09	19.70	3.30
Daring Lake	Ld5	Low	24.51	63.52	47.56	6.34	6.02	5.95	10.55	2.59
Daring Lake	Ld0	Low	21.47	68.62	51.06	6.87	6.09	3.82	11.27	3.20
Daring Lake	Ue15	Up	27.70	43.45	29.68	7.19	16.85	12.00	2.58	1.57
Daring Lake	Ue10	Up	28.07	51.41	34.00	8.66	14.67	5.86	3.51	1.83
Daring Lake	Ue5	Up	21.41	36.28	25.14	4.87	22.28	20.03	1.63	1.69
Daring Lake	Ue0	Up								
Daring Lake	Be15	Back	30.83	51.59	35.88	8.35	12.32	5.25	4.19	1.67
Daring Lake	Be10	Back	24.03	52.09	35.21	8.15	16.98	6.91	3.07	2.17
Daring Lake	Be5	Back	31.69	47.45	35.30	5.26	12.20	8.66	3.89	1.50
Daring Lake	Be0	Back	29.72	56.67	39.47	9.78	9.75	3.87	5.81	1.91
Daring Lake	Le15	Low	24.17	64.92	47.90	7.21	6.85	4.06	9.48	2.69
Daring Lake	Le10	Low	28.21	55.96	40.22	7.00	10.22	5.61	5.47	1.98
Daring Lake	Le5	Low	20.97	68.01	51.40	5.19	7.11	3.91	9.57	3.24
Daring Lake	Le0	Low								
Truelove	TU1	Up	26.03	54.65	36.05	10.97	10.91	8.42	5.01	2.10
Truelove	TU2	Up	19.99	52.53	33.91	10.08	15.65	11.84	3.36	2.63
Truelove	TU3	Up	19.40	50.50	31.75	9.62	17.90	12.20	2.82	2.60
Truelove	TU4	Up	18.47	55.87	36.49	9.70	16.37	9.29	3.41	3.02
Truelove	TU5	Up	18.78	53.77	35.82	8.77	15.83	11.62	3.40	2.86
Truelove	TU6	Up	19.73	55.74	36.83	9.42	15.19	9.34	3.67	2.83
Truelove	TU7	Up	23.75	54.29	36.30	9.81	12.43	9.54	4.37	2.29
Truelove	TU8	Up	22.97	54.00	34.22	10.77	15.78	7.26	3.42	2.35
Truelove	TU9	Up	20.22	56.75	36.67	10.71	14.41	8.62	3.94	2.81
Truelove	TU10	Up	24.21	57.73	38.88	10.58	10.92	7.14	5.29	2.38
Truelove	TB1	Back	21.80	56.22	37.06	10.49	12.92	9.06	4.35	2.58
Truelove	TB2	Back	21.94	54.60	35.27	10.57	14.97	8.49	3.65	2.49
Truelove	TB3	Back	19.60	56.34	37.19	10.03	14.67	9.39	3.84	2.87
Truelove	TB4	Back	22.64	54.93	35.43	11.22	14.20	8.24	3.87	2.43
Truelove	TB5	Back	19.33	52.27	33.80	9.54	16.73	11.67	3.12	2.70
Truelove	TB6	Back	23.19	58.05	38.57	11.47	11.53	7.23	5.03	2.50
Truelove	TB7	Back	21.33	54.54	34.94	10.81	15.70	8.43	3.48	2.56
Truelove	TB8	Back	20.05	56.21	37.24	9.81	14.05	9.69	4.00	2.80
Truelove	TB9	Back	25.42	57.34	37.44	12.15	10.40	6.84	5.51	2.26
Truelove	TB10	Back	22.89	57.53	38.33	10.93	11.57	8.02	4.97	2.51
Truelove	TL1	Low	22.51	53.22	35.01	10.03	14.00	10.27	3.80	2.36
Truelove	TL2	Low	24.15	57.98	38.23	11.60	10.73	7.15	5.41	2.40
Truelove	TL3	Low	18.41	53.95	35.23	9.93	17.33	10.32	3.11	2.93
Truelove	TL4	Low	11.21	38.49	24.69	4.12	32.67	17.63	1.18	3.43
Truelove	TL5	Low	19.63	55.14	36.06	10.35	15.59	9.64	3.54	2.81

Ecosystem	Point	Topo	AC	OAC	CC	MC	AroC	CbyC	OAC : AroC	OAC : AC
			%	%	%	%	%	%		
Truelove	TL6	Low	26.32	57.83	36.34	13.36	13.63	2.21	4.24	2.20
Truelove	TL7	Low	21.71	59.67	40.46	10.66	10.68	7.94	5.58	2.75
Truelove	TL8	Low	21.70	57.88	39.07	10.18	12.85	7.58	4.51	2.67
Truelove	TL9	Low	17.56	58.90	38.59	10.16	16.65	6.88	3.54	3.35
Truelove	TL10	Low	11.84	62.38	45.07	5.21	15.97	9.81	3.91	5.27
Truelove	W1.1	Wedge	21.12	55.39	37.56	8.53	14.19	9.30	3.90	2.62
Truelove	W1.2	Wedge	25.04	57.48	38.54	10.39	10.87	6.61	5.29	2.30
Truelove	W2.1	Wedge	21.33	57.07	38.96	8.59	13.06	8.54	4.37	2.68
Truelove	W2.2	Wedge	30.01	56.70	38.54	10.17	8.72	4.57	6.50	1.89
Truelove	W3	Wedge	32.01	54.72	36.88	10.61	8.57	4.70	6.39	1.71
Truelove	W4	Wedge	16.24	67.25	49.24	6.73	8.67	7.84	7.75	4.14
Truelove	W5	Wedge	30.53	50.81	33.04	10.06	11.62	7.04	4.37	1.66
Truelove	W6	Wedge	15.41	67.92	49.60	6.45	9.44	7.23	7.20	4.41
Truelove	W7	Wedge	18.65	57.93	39.92	8.07	14.22	9.21	4.07	3.11
Truelove	W8	Wedge	26.59	53.83	35.83	9.34	11.62	7.96	4.63	2.02
Truelove	W9	Wedge	24.49	52.71	34.94	8.83	14.09	8.70	3.74	2.15
Truelove	W10	Wedge	14.89	63.00	45.74	5.89	13.24	8.87	4.76	4.23
Truelove	P1.1	Hummock	27.93	56.30	37.53	10.78	9.60	6.17	5.87	2.02
Truelove	P1.2	Hummock	21.98	53.85	36.14	8.42	14.13	10.03	3.81	2.45
Truelove	P2.1	Hummock	23.22	53.14	34.87	10.18	13.39	10.24	3.97	2.29
Truelove	P2.2	Hummock	27.96	54.16	35.79	10.81	10.17	7.71	5.32	1.94
Truelove	P3	Hummock	23.92	56.76	37.13	11.50	11.99	7.33	4.73	2.37
Truelove	P4	Hummock	21.12	58.04	38.49	10.16	13.70	7.14	4.24	2.75
Truelove	P5	Hummock	28.26	54.44	35.66	11.00	10.31	6.99	5.28	1.93
Truelove	P6	Hummock	27.55	56.07	37.26	10.78	10.37	6.01	5.41	2.04
Truelove	P7	Hummock	23.49	56.58	37.92	9.76	12.35	7.58	4.58	2.41
Truelove	P8	Hummock	29.06	54.07	35.71	10.53	10.16	6.71	5.32	1.86
Truelove	P9	Hummock	25.77	53.41	34.96	10.03	12.26	8.56	4.36	2.07
Truelove	P10	Hummock	26.83	57.82	39.03	10.32	9.46	5.89	6.12	2.16

Appendix G: Soil Profiles

Table G 1: Soil profiles at Churchill

Site	Topo	Horizon	Depth	Rooting zone	Van Post Scale	Color	Rubbed Fiber
			cm	cm			%
Dump	Upper	Ah	0-23	0-50			
		C1	23-42				
		C2	42-45				
		C3	45+				
	Back	Om	0-10	0-26	[5-6]	10YR22	40
		C	10+				
	Lower	Of	0-6	0-50	3	7.5YR2.5-2	70
		Om	6-24		[5-6]	10YR2-1.5	40
		C	30-40				
		Cg	40+				
Buggy	Upper	Ah	0-5	0-38			
		C1	5-30				
		C2	30-37				
		C1	37+				
	Back	Ofm	0-3	0-40	3	7.5YR2.5-2	50
		Cummulic	3-32				
		C1	40+				
		OM pocket	60-63				
	Lower	Om	0-15	0-30	5	7.5YR2.5-2	50
		Cummulic	15-30				
		Cg	30+				
Bear	Upper	Ah	0-15	0-40			
		C1	15-26; 30-35; 40+				
		C2	26-30; 35-40				
	Back	Ah	0-19	0-55			
		C1	19-50; 55+				
		C2	50-55				
	Lower	Om	0-20	0-50	7	10YR2-1	25
		BC	20+				
		OM pocket	50				
Hummock	Wedge	Of	0-6	0-25	[4-5]	7.5YR2.5-2	45
		Ofm	6-7		7	10YR2	20
		C	7+				
	Hummock	Of	0-10	0-60	2	7.5YR2.5-3	90
		Om	10-43		7	10YR2-1	20
		C	43+				

Table G 2: Soil profiles at Daring Lake

Site	Topo	Horizon	Depth	pH	OC	Carbonates
			cm		%	%
Saguenay	Upper	LFH	2-0	5.05	8.51	0.05
		Ahe	0-7	5.19	1.45	0.06
		Bm	7-20	5.2	0.83	0.05
		BC	20-30	5.28	0.30	0.06
		C	30+	5.3	0.08	0.05
	Back	LFH	2-0	4.29	28.26	0.16
		Ah-Ae	0-20	5.07	0.75	0.05
		Bm	20-55	5.57	0.36	0.07
		Cg1	45-75	5.79	0.07	0.04
		Cg2	75-98	5.84	0.04	0.04
		Cz	98+			
	Lower	OM	0-20			
		C	20-100	5.06	0.70	0.05
		Ah (lens)	70-75 (OM pocket)		13.02	0.08
		Cz	100+	5.23	0.73	0.06