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# Influence of site and soil properties on the DRIFT spectra of northern cold-region soils

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ABSTRACT

We investigated the influence of site characteristics and soil properties on the chemical composition of organic matter in soils collected from a latitudinal transect across northern cold-region through analysis of diffuse reflectance Fourier transform mid infrared (DRIFT) spectra of bulk soils. The study included 119 soil samples collected from 28 sites including tundra, boreal forest, grassland, and coastal rainforest ecosystems. Organic, mineral, and cryoturbated soil horizons, both seasonally and perennially frozen, representing a variety of depths and edaphic conditions were examined. The amount and chemical composition of organic matter, as well as site and soil properties, exerted a strong influence on the DRIFT spectra. The spectra were highly sensitive to the extent of organic matter decomposition, enabling the ordination of organic (Oi, Oe and Oa) horizons. Differences in absorbance intensity for several spectral bands indicated that Oi horizons contained greater abundance of relatively fresh residues, phenolic-OH compounds, aliphatic compounds, and carbohydrates. In contrast, Oa horizons had a greater presence of amide groups, aromatics, C═C bonds, carboxylates and carboxylic acids. Another significant factor differentiating these horizons was the incorporation of clays and silicates into the Oa horizons. Calculated ratios of characteristic spectral bands showed a clear trend of increasing decomposition from Oi to Oe to Oa. The DRIFT spectra were related to many site/soil attributes including land cover type, parent material, and associated factors, such as permafrost presence/absence, drainage class, horizon depth, bulk density, cation exchange capacity, and pH. A single DRIFT spectral band was identified that might be used in future studies to quickly estimate the organic carbon, total nitrogen, and carbon:nitrogen ratios of northern soils. Our results demonstrate that the information contained in DRIFT spectra of soil integrates the quantity and chemical composition of soil organic matter with soil properties and highlights the potential for using this information to assess the degradation state of organic matter stored in northern cold-region soils.

## 1. Introduction

Soils in arctic and subarctic regions contain large amounts of organic matter that accumulated over millennia, largely due to environmental factors limiting microbial activity (Hugelius et al., 2014; Tarnocai et al., 2009). Now, climatic change is causing region-wide warming, permafrost degradation, hydrologic changes, and other related disturbances with potential implications for the persistence of the organic matter stored in the region's soils (Brown et al., 2015; Jorgenson et al., 2010; Romanovsky et al., 2010; Rowland et al., 2010; Schuur et al., 2015). Thus, improved understanding of the relationships between environmental factors and regional soil organic matter (SOM) stocks and their potential decomposability is of great importance for predicting SOM responses to changing climatic conditions (Mishra et al., 2013).

The combined effects of soil forming factors (climate, parent material, organisms, topography and time) determine soil development and the characteristics that impact SOM stocks and their vulnerability to environmental changes. Climate, especially low temperatures, is one of the most influential factors affecting the formation of northern soils (Johnson et al., 2011; Ping et al., 2015). In the case of Gelisols (soils underlain by permafrost), soil formation is greatly shaped by unique cryopedogenic processes driven by the combination of low temperatures, water movement, and freeze-thaw cycles (Ping et al., 2015). For

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example, fresh organic materials can be buried and mixed with mineral soil at depth through the process of cryoturbation produced by frost heave, cracking, and churning (Bockheim, 2007; Kaiser et al., 2007; Michaelson et al., 2008; Ping et al., 2008a,b; Tarnocai and Smith, 1992). Low temperatures, sometimes coupled with saturated and reducing conditions and/or acidic microenvironments, can also lead to greater storage of relatively fresh SOM than is found in more temperate regions because the SOM is preserved by slowed decomposition rates (Diochon et al., 2013; Mueller et al., 2015; Pedersen et al., 2011; Xu et al., 2009a). Parent material and weathering processes determine soil mineralogy and other properties affecting the composition and stability of SOM (Mitchell and Soga, 2005). Soils in the northern cold-region mostly formed on sediments deposited by water (alluvium), wind (loess) and glaciers (outwash, moraine or drift), residuum (in-situ weathering of bedrock) and volcanic deposits (tephra). As a result, soils with distinct chemical characteristics related to differing parent materials have developed over time (Ping et al., 1998, 2017). Arctic and subarctic soils support a wide variety of vegetative communities including coniferous and deciduous forest, dwarf and low shrubs, and a variety of tundra types and wetlands (Chapin et al., 2006; Walker et al., 2005). Vegetation type affects the chemical composition of litter inputs and SOM. For example, marked differences in species composition exist between acidic and non-acidic tundra (Walker et al., 2005), which are related to differences in the quantity and chemical composition − functional groups and molecules − of SOM under those vegetation types (Xu et al., 2009a,b). Topography, slope position, and aspect play a significant role in northern soil formation via localized influences on soil hydrology, temperature, and related controls on vegetative community composition (Chapin et al., 2006; Ping et al., 2015).

A number of studies have investigated the relationships of edaphic and environmental factors to the storage and distribution of organic carbon in northern cold-region soils (e.g., Hugelius and Kuhry, 2009; Johnson et al., 2011; Mishra and Riley, 2012; Ping et al., 2008b). Yet, detailed information is lacking on how such factors influence the chemical composition of SOM, which is needed to improve predictions of cold-region SOM responses to environmental perturbations (Hugelius et al., 2012; Kuhry et al., 2013; Purton et al., 2015; White et al., 2004). For example, upon finding only small differences in the chemical composition of SOM across a latitudinal climosequence spanning the boreal forest-prairie ecotone in west-central Saskatchewan, Canada, Purton et al. (2015) concluded that within profile processes appeared to have greater effects on SOM composition than processes operating at landscape and regional scales. However, this climosequence was relatively limited (46 km) in extent. In many instances local-scale patterns can have regional-scale impacts. For example, similarities in chemical composition between SOM in the upper permafrost and active-layer organic horizons confirm that relatively fresh organic materials can be incorporated and preserved in the upper permafrost via cryoturbation. This within-profile process has potential implications for the heterogeneity of SOM composition across the permafrost region (Ernakovich et al., 2015; Ping et al., 2015; Xu et al., 2009a). Further, Baldock et al. (1992, 1997) found that both large scale (soil order – the highest classification category of soil taxonomy) and fine scale (soil particle size) factors were strongly related to the chemical composition, degree of decomposition, and bioavailability of SOM.

Indeed, the chemical composition of SOM has been used to assess and compare its relative degradation state and potential decomposability in both organic and mineral soils. Generally, the proportions of carbohydrates decrease and aliphatics increase as peat decays, while the trends observed in other moities, such as aromatics, can vary depending on vegetative composition and other factors (Hodgkins et al., 2014; Preston et al., 1987; Sjögersten et al., 2016). Similar increases in the proportion of aliphatic carbon on mineral particle surfaces have been associated with greater SOM degradation in mineral soils (Baldock et al., 1992; Feng et al., 2016). The chemical composition of SOM in northern soils shows evidence that microbial processing is occurring, even under anaerobic and cold conditions. Microbial products such organic acids and carboxylates (Pérez et al., 2002) have been found in both active layer and permafrost horizons (e.g. Ernakovich et al., 2015). Thus, characterization of SOM composition, including the relative depletion or accumulation of certain organic compounds, may help to discern key factors affecting the size and degradation state of SOM stocks at landscape and regional scales and their susceptibility to climatic change and related disturbances (Feng and Simpson, 2011).

Previous studies of soils across Alaska and Canada have provided a wealth of information from different bioclimatic zones that vary in permafrost presence (continuous or discontinuous), land cover type, SOM content, and many other soil physical and chemical characteristics (e.g., Michaelson et al., 2013; Ping et al., 1997, 2008a). The archived samples associated with these studies provided the opportunity to investigate which site and soil characteristics are most strongly related to variations in the chemical composition of SOM for a wide range of northern cold-region soils. In this study, we obtained DRIFT spectra for a large number of soil samples – collected from pedons along a latitudinal transect across Alaska and Canada – that are well characterized in terms of site attributes and soil physical and chemical properties. Our objectives were to assess the suitability of DRIFT spectroscopy to distinguish properties specific to northern cold-region soils, and identify whether characteristic spectral bands can be used to resolve the extent of SOM decomposition in these soils.

## 2. Materials and methods

### 2.1. Site locations and site/soil characteristics

Study soils were collected from 27 sites across Alaska, U.S.A. and one site on Ellef Ringness Island, Nunavut, Canada. The sites are distributed along a latitudinal gradient from 55.3525°N to 78.7858°N with longitudes that varied from 103.5519°W to 151.7339°W and extending across 2800 km (Table 1). The sites were sampled from 1981 through 2008 for various projects, and all soil samples were processed and archived at the University of Alaska Fairbanks. The soil profiles were described and samples were taken by horizon from the exposed profiles of soil pits according to Soil Survey Division Staff (1975) and Soil Survey Staff (1999). The nomenclature of soil horizons were updated according to Schoeneberger et al. (2012) and Ping et al. (2013). A subset of 119 samples were selected from this archive to provide a wide range of site and soil characteristics for this study.

Seven categorical factors describing site/soil physical attributes (land cover, parent material, soil drainage class, horizon, horizon depth, permafrost presence/absence, and cryoturbation presence/absence) were determined in the field for each sample (Table 1). Across the sites, forests (53%) and tundra (36%) were the dominant land cover types, while grasslands and shrublands were less abundant. The sites differed greatly in parent material, which included alluvium, colluvium, glacial drift, glaciomarine sediments, glacial outwash, lacustrine deposits, loess, glacial moraine and tephra. Colluvium, glacial moraine, and tephra were exclusively found at forest sites, while glacial drift was only present at tundra sites. The other parent materials were associated with various land cover types. Poorly drained soils occurred at 44% of the forest sites, but the majority of tundra sites, 90%, were poorly drained. Of the sampled soils included in the dataset, 27% were designated as organic horizons and 73% as mineral horizons. About 17% of the soils were collected from permafrost and 13% were cryoturbated, the majority of which were from tundra sites (Table 1).

Samples were also analyzed for 16 quantitative factors characterizing soil chemical/physical properties (Table 2). Bulk density (BD) measurements were obtained by methods appropriate to specific horizon types including the clod method (Soil Survey Staff, 2014) and measured dimensional block and core volume methods (Ping et al., 2013), adjusting for coarse fragments. Prior to other analyses, samples were air-dried at room temperature and passed through a 2-mm sieve to