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Soils and frost boil ecosystems across the North American Arctic Transect

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[1] We studied soil properties of frost boils at nine zonal-vegetation locations across the North American Arctic Transect (NAAT) in order to better understand arctic soils and their interaction with other biogeophysical components of frost boil ecosystems. Soil genetic horizons were analyzed for particle size, pH, electrical conductivity, total organic carbon (OC) and nitrogen (N), bulk density and volumetric water content. Surface soils (0–5 cm) across frost boil patterns were analyzed for of pH, OC, water content, extractable N and P, and exchangeable K, Ca and Na. Our results revealed that soil texture, pH, EC, P, Na and Ca contents are strongly influenced by local parent materials. Soil pH was acidic in the north going to alkaline in the midtransect and then again back to acidic in the south. Simple correlations between soil analytical data and observed frost boil properties across the NAAT support and are consistent with the laboratory and theoretical-conceptual models of pattern ground dynamics that have been developed by others. Soil water related well to texture. Soil horizon %OC and profile OC stocks under the pattern corresponded well to biomass and frost heave, respectively. Also soil water was closely related to biomass and heave. Nutrients in surface soils at sites corresponded to OC stocks. An interaction between soil water and segregation of Na and Ca between the pattern and interpattern was found for locations with high cation availability. At these sites, chemical as well as physical disruption of the pattern area could affect plant establishment. Overall there was a good linkage between properties relating to frost boil pattern dynamics and soil biogeochemical properties. Our study offers insight into the important process of cryoturbation for carbon sequestration in Gelisols across the Arctic.

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1. Introduction

[2] The presence of pattern ground features including frost boils is perhaps the most unique element of the arctic landscape. These features have been recognized, studied and classified for many years [*Washburn*, 1980]. But more recently these features have been recognized for their importance in organic carbon (OC) sequestration through cryoturbation [*Michaelson et al.*, 1996; *Ping et al.*, 1998]. With the Arctic being in the forefront of climate change impacts and holding large amounts of the terrestrial OC stocks there is a need to better understand these features and their role in the ecosystem in relation to changing climate [*IPCC*, 1992; *Walker et al.*, 2004]. Organic carbon dynamics in the Arctic is dependant on the key interactions between soil properties and development of the biotic-vegetation community [*Hobbie et al.*, 2000]. However, a bioclimatic gradient exists across the Arctic [*Walker et al.*, 2003] and thus climate changes will likely have varying affects on organic carbon sequestration in permafrost affected soils - Gelisols. Examination of the biogeophysical elements affecting the complex frost boil ecosystems across the broader arctic bio-climatic gradient will be necessary to understand or predict future changes. Climate changes over time will impact the arctic biological communities and frost boil dynamics in ways that could be similar to the way observed today across the existing Arctic gradient with regard to the interactions in biogeophysical elements and system dynamics.

[3] Development and maintenance of frost boils is heavily dependant on soil properties and the success of vegetation establishment on surface soils [*Walker et al.*, 2004]. Initial pattern formation and spacing is dependent on active layer thickness and availability of soil profile water to move to seasonal freezing fronts [*Peterson and Krantz*, 2003; *Peterson et al.*, 2003]. Therefore soil characteristics such as water content and distribution, texture and depth to permafrost become important to pattern expression and persistence. Patterning creates microenvironments at the soil

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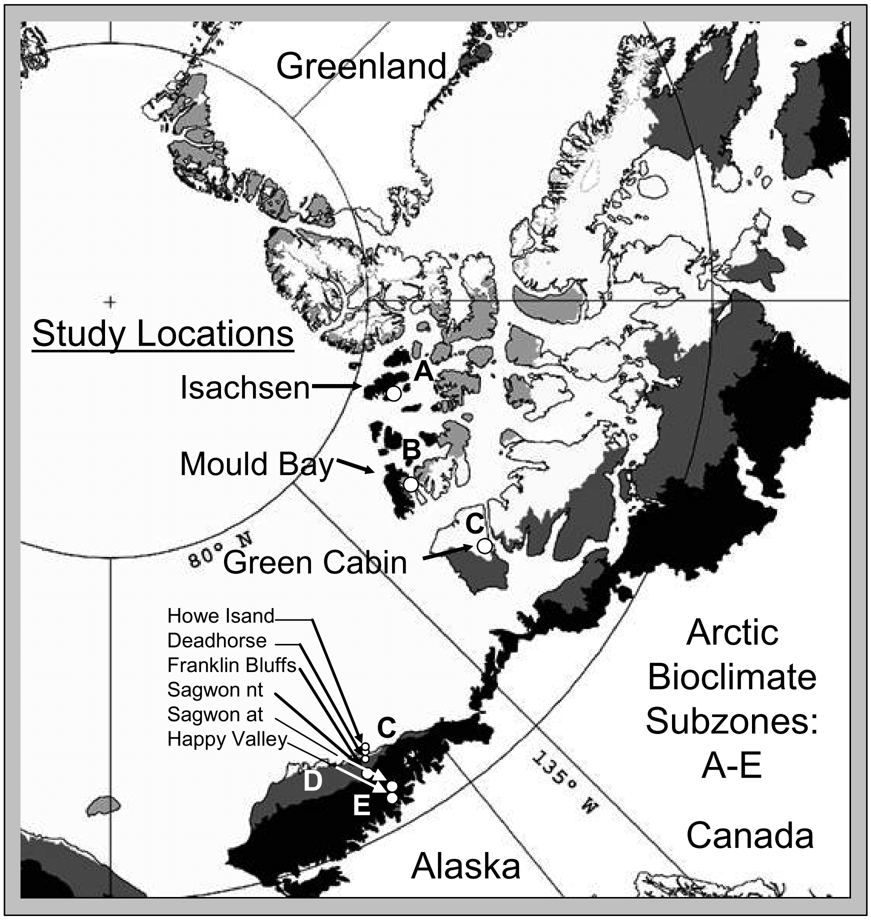

Figure 1. Map of North American Arctic Transect (NAAT) with bioclimatic subzones [*Walker et al.*, 2005].

surface that has varying degrees of stability and suitability for establishment of biota and vegetation. The success of biota/vegetation and the build-up of organic matter and nutrients in the surface microenvironments can in turn affect the dynamics of the ground-pattern. The effects of biota/vegetation are through controls on soil moisture and surface thermal characteristics [*Kade and Walker*, 2008]. Therefore variations in soil fertility as biota establishes across the surface of patterns are important to the success of vegetation and ultimately patterned ground dynamics.

[4] We conducted a detailed study of soils associated with frost boils on zonal vegetation sites across the North American Arctic Transect (NAAT, *Walker et al.*, 2008) that included the full range of arctic Bioclimatic Subzones [*Walker et al.*, 2003, 2008]. The objective of this study is twofold first, to examine the range and distribution of both whole soil profile and surface soil properties. Second using the existing conceptual framework for frost boil dynamics we explore simple relationships among soil properties and frost boil characteristics using our NAAT data. We seek to better understand the nature of the biological-chemical-physical interactions that occur with pattern expression using actual measured soil properties over the full range of arctic conditions. A better understanding of these interactions as they exist today across a gradient is especially pertinent to understanding and future modeling of the OC dynamics and the biological consequences of climate change across the system.

2. Methods

2.1. Soils

[5] Soils were sampled in conjunction with the NSF-Biocomplexity of Frost-boil Ecosystems project and detailed location information can be found in *Walker et al.* [2008] and *Raynolds et al.* [2008]. General locations of the nine sampling plots can be seen on the map (Figure 1). See Table S1 for GPS coordinates (available as auxiliary material).[1] Samples were taken from soil horizons delineated in a pit [*Soil Survey Staff*, 1993] excavated to a 1-m depth with approximate dimensions of 2 by 1-m length and width. Soil pits were placed to dissect the complete frost boil pattern cycle from interpattern area to the frost boil pattern center (results in Figures 2 and 3). Dimensional measured samples were also taken that consisted of either blocks or volume cores removed from each horizon to be used for bulk density and volumetric water content determinations. These samples represented the whole soil profile under frost boils (nonsorted circles) across the full pattern cycle. Samples representing soil surface layers (0–5 cm depth)

[1] Auxiliary materials are available in the HTML. doi:10.1029/2007JG000672.

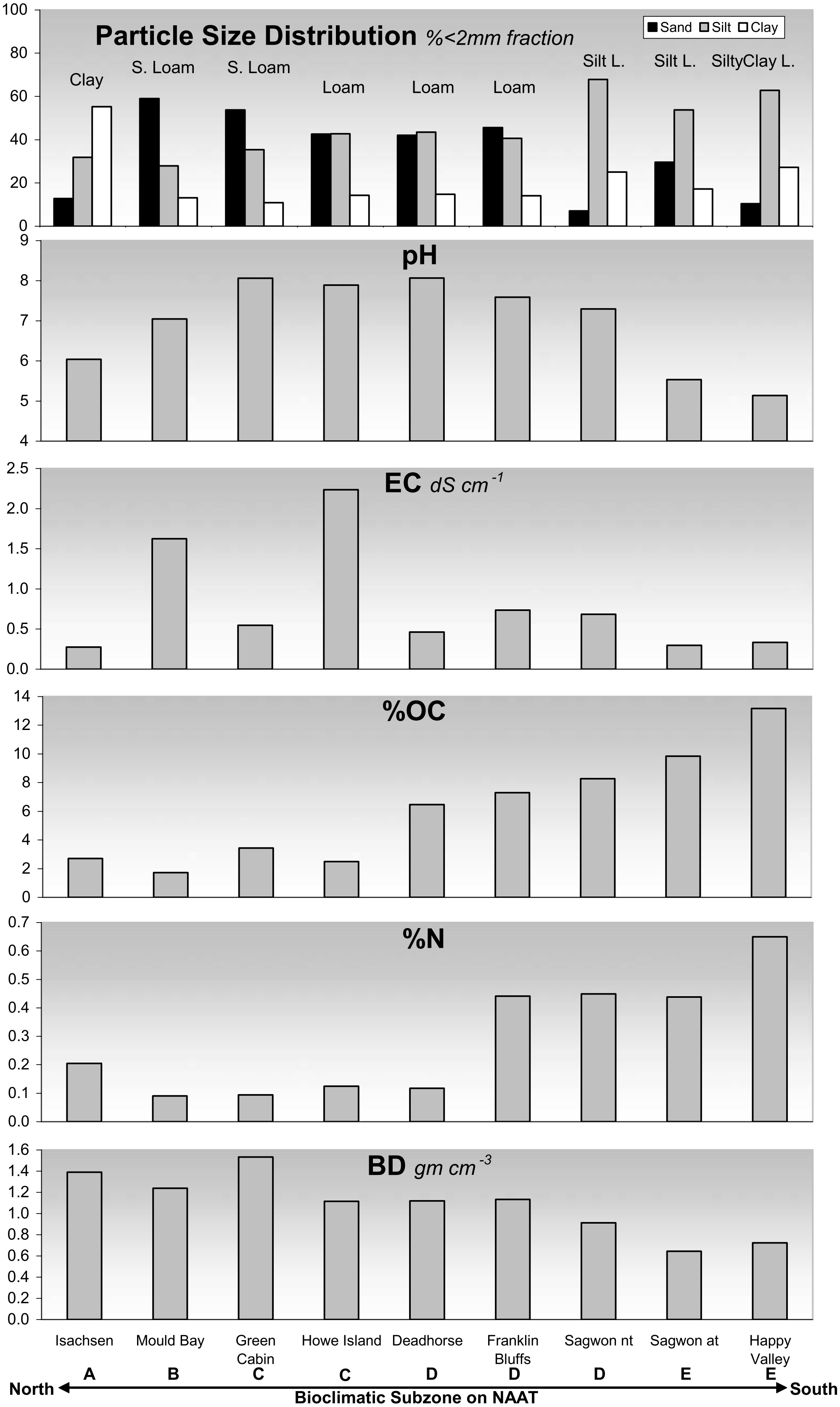

Figure 2. Selected average soil properties for profiles (to 1 m depth) of the zonal vegetation sites along the North American Arctic Transect (NAAT) with bioclimatic subzones according to *Walker et al.* [2005]. Averages are weighted sum of properties using relative horizons thicknesses as identified from the soil pit exposures to 1 m [*Michaelson et al.*, 1996].

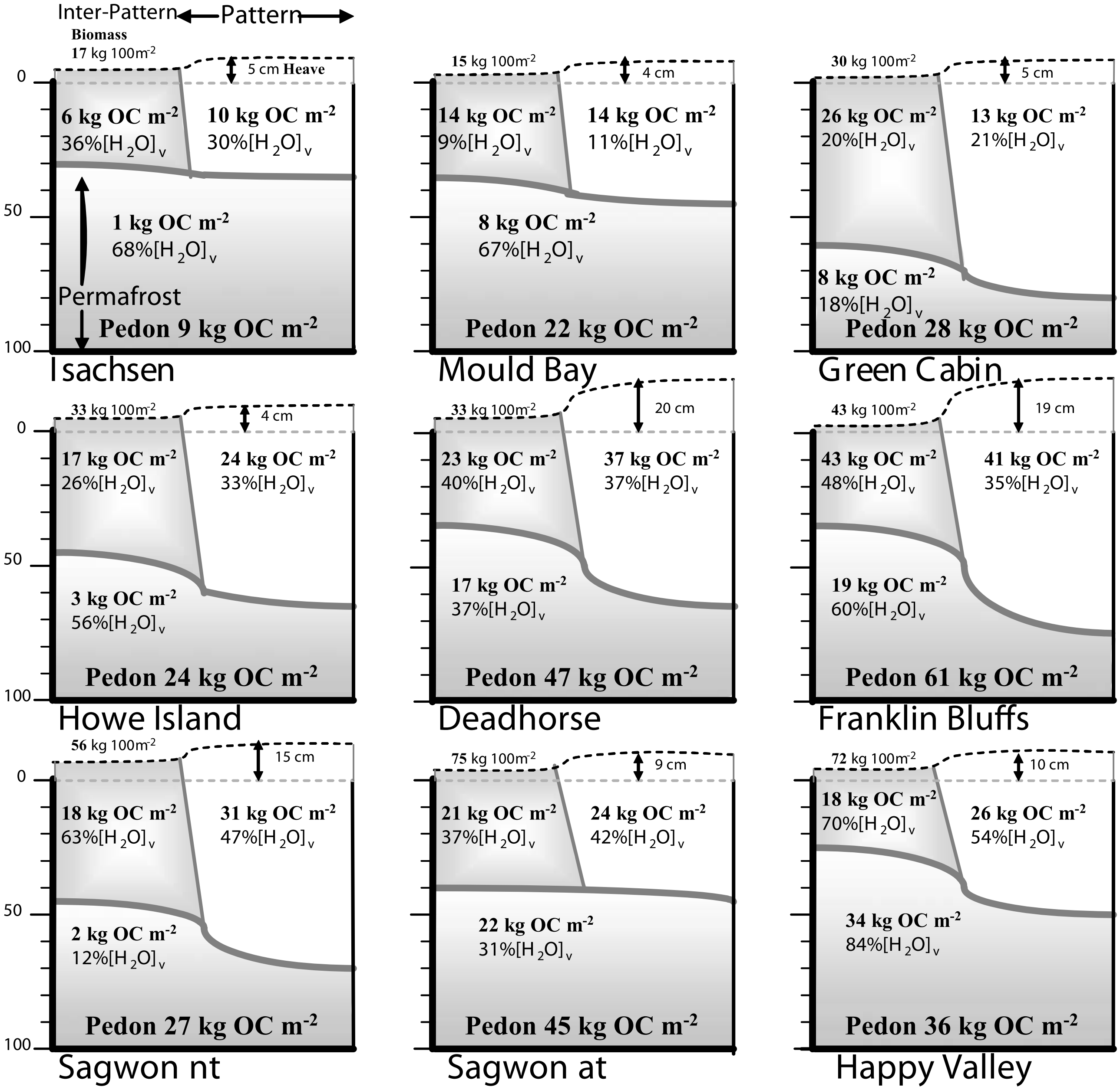

Figure 3. Schematic cross-sections of soil profiles under frost boils at zonal vegetation locations along the NAAT. Each profile diagram has three zones (compartments) representing the active-layer interpattern, the active-layer pattern, and the permafrost to 1 m depth. The soil OC (organic carbon) and volumetric percentage water contents ($[H_2O]_v$) were measured in this study and are calculated from horizon samples data (Table S1). Biomass and soil heave (interpattern/pattern) are from *Raynolds et al.* [2008]. Surface differential heave is given in centimeters and represented by the offset dashed line on the top of each diagram.

were also collected from the interpattern and pattern center areas separately. These samples were used in the nutrient fertility related analysis. These surface samples were collected by slicing measured dimension blocks using a knife. The blocks were collected and used for bulk density, water content and fertility measurements (results: Figure 4).

2.2. Soil Analysis

[6] Bulk density and volumetric water content were determined from field-moist volume samples dried to 100°C. Soil particle-size distribution and texture were determined using the hydrometer method and the USDA textural class triangle [*Gee and Bauder*, 1986]. Soil pH was by saturated paste method using a combination pH electrode and electrical conductivity was determined on the paste extract using a platinum cell. Total organic carbon and nitrogen were by LECO CHN-Analyzer on an air-dried sample (inorganic carbon removed by HCl) with correction to 100°C dry weight.

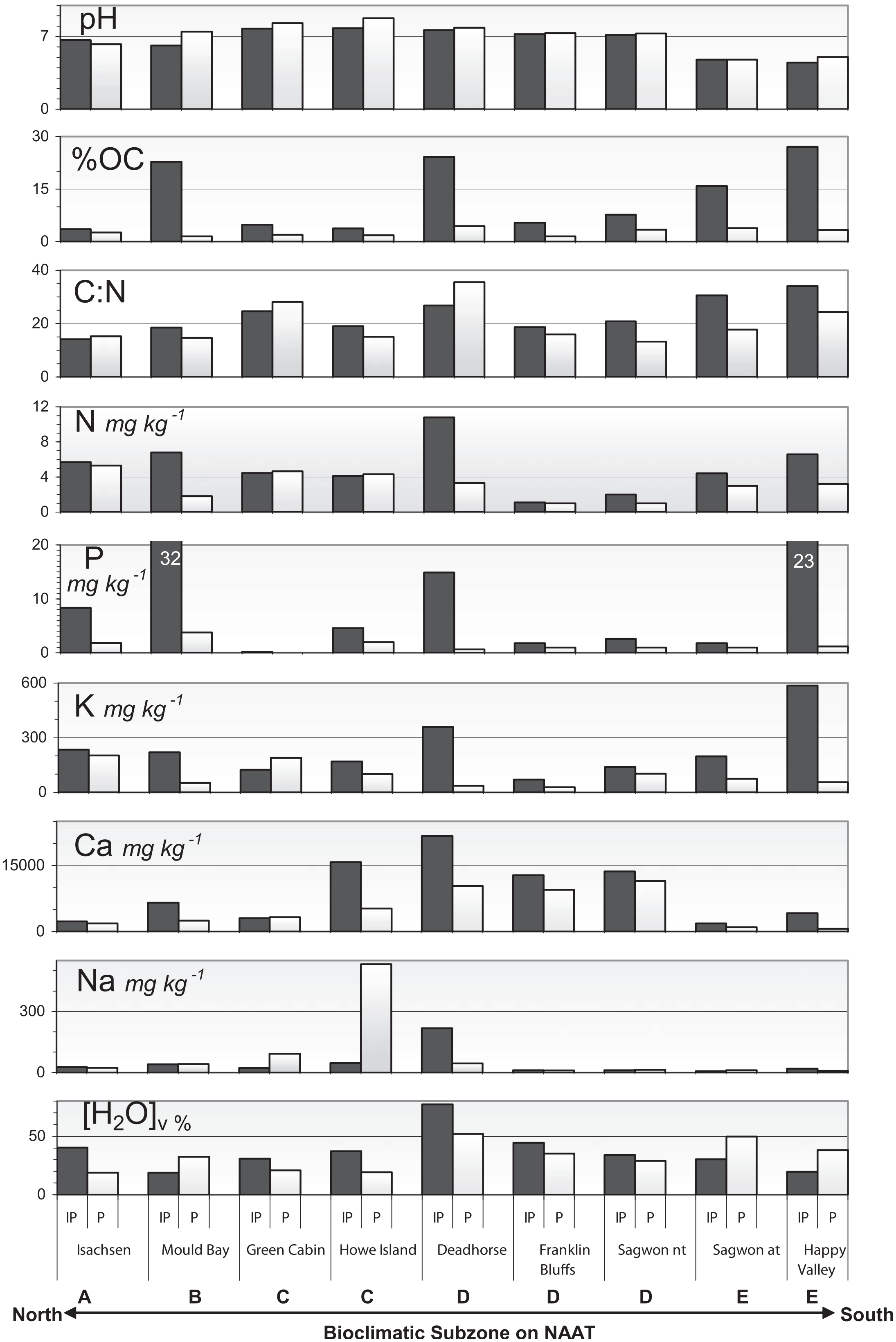

Figure 4. Selected properties of surface soil (0–5 cm): pH, total organic carbon (%OC), total OC to total N ratio (C:N), content of exchangeable major plant nutrients; nitrogen (N), phosphorus (P), potassium (K), Calcium (Ca) and sodium (Na), and percentage volumetric water content ($[H_2O]_v$) along the NAAT zonal vegetation locations. Inter Pattern surfaces sampled are given as IP (vegetated areas) adjacent to the pattern P areas (minimally vegetated or barren boil centers).

[7] Extractable nitrogen was by 2M KCl (1:10) extraction with ammonium plus nitrate nitrogen determination by Autoanalyzer colorimetric methods. Phosphorus was by Mehlich-3 [*Mehlich*, 1984] extraction and determination using a Model 1000 Perkin-Elmer inductively coupled plasma spectrophotometer. The cations K, Ca, and Na were extracted by neutral 1M ammonium acetate and determined using a Model 1000 Perkin-Elmer inductively coupled plasma spectrophotometer.

3. Results

3.1. Whole Profiles

[8] Figure 2 summarizes selected soil profile characteristics for all horizons averaged across patterned ground features (to 1 m depth) on the zonal vegetation plots (individual horizon data given in Table S1). Schematic diagrams of the features at each location are in Figure 3. Soil textures ranged from fine-textured clay soils at the northernmost Isachsen site with clay content from 47 to 60%, to coarser sandy loams at Mould Bay and Green Cabin, medium textured loam soils at the northern Alaska sites of Howe Island, Deadhorse and Franklin Bluffs, silt loams at the two Sagwon sites (Sagwon-nt = nonacidic tundra and Sagwon-at = acidic tundra site) and silty clay loam at the southernmost Happy Valley site. Active layers within each site have fairly narrow ranges in particle size distribution. They consisted of horizons that were all clays (Isachsen), sandy loams silt loams or loams (Mould Bay through Sagwon) or silt loams mixed with silty clay loam at Happy Valley. Coarse fragments greater than 2 mm size were generally less than 1% except for the Isachsen site where they ranged from 0.2 to 9.7%, the Mould Bay site where they ranged from <0.1 to 6%, the Green Cabin site where they ranged from 1 to 27%, and the Sagwon-at where they ranged from 1.4 to 4% (Table S1).

[9] Soil pH (Figure 2) averaged slightly acidic in the north at Isachsen (pH = 6) to neutral and alkaline moving south to the Sagwon-nt (pH range: 7.0–8.1) and then acidic for the southernmost Sagwon-at and Happy Valley soils (pH = 5.5 and 5.1 respectively). Average electroconductivity (EC) values of the acidic locations were lowest with Isachsen, Sagwon-at and Happy Valley at 0.27, 0.30 and 0.33 dS cm^{-1}. The highest average EC values were at the Mould Bay and Howe Island sites at 1.63 to 2.24 dS cm^{-1} respectively. There was an increasing north to south trend in both average soil total organic carbon (OC) and nitrogen (N) content of soils. The more northern bioclimatic subzone (A-C) sites of Isachsen to Howe Island ranged from an average of 1.7 to 2.5% TOC while the more southern sites of Franklin Bluffs to Happy Valley averaged 6.5 to 13.2% TOC. Average soil N was lower in the north for Isachsen through Deadhorse ranging from 0.09 to 0.20 while southern sites of Franklin Bluffs through Happy Valley ranged higher at 0.44 to 0.65% N. Conversely, soil field bulk density (BD) decreased from north to south on the transect, going from an average ranging from 1.24 to 1.53 g cm^{-3} in the northern three sites to 0.65–0.91 g cm^{-3} for the southernmost three sites.

[10] The Schematic diagram in Figure 3 presents our measurements for interpattern/pattern (IP/P) active layer depths, volumetric water content ($[H_2O]_v$) and organic carbon stocks (kg OC m^{-2}) averaged for profile cross sections into the permafrost. Also noted at the top of each profile diagram are biomass (left top) and heave (right top) measurements taken from *Raynolds et al.* [2008] for the same NAAT sites. Stocks of OC ranged from a low of 9 to a high of 56 kgOC m^{-2} in the soils at Isachsen and Happy Valley respectively. Active layer OC ranged from 8 to 43 kg OC m^{-2} for the Isachsen and Franklin Bluffs profiles respectively, while permafrost OC ranged from 1 to 34 kg OC m^{-2} for the Isachsen and Happy Valley profiles respectively. Partitioning within the interpattern/pattern active layer varied with little difference for the Mould Bay, Franklin Bluffs and Sagwon-at profiles (all within 0–13%). There was more OC in the interpattern active layer relative to pattern active layer at Green Cabin (67% more), and more OC in the pattern active relative to interpattern active layer at Isachsen, Howe Island, Deadhorse, Sagwon-nt, Sagwon-at, and Happy Valley (50, 34, 47, 53, 13, and 36% higher respectively). Volumetric water contents of the permafrost ranged from 12 to 84% for the Sagwon-nt and Happy Valley profiles respectively. Active layer water contents ranged from 9 to 70% for the Mould Bay and Happy Valley profiles respectively. Partitioning of water between the interpattern/pattern sections of the profiles ranged from 5 to 31%.

3.2. Surface Soil

[11] Parameters important to soil fertility of the upper rooting zone (0–5 cm, interpattern/pattern, IP/P) are presented in Figure 4. Soil pH varied from slightly acidic (IP/P: pH = 6.7/6.3) on the northern Isachsen end of the NAAT to the highest alkaline levels in the midtransect Howe Island location (IP/P: pH = 7.8/8.8) and then dropped to the acidic range at the southern two locations of Sagwon-at (IP/P: pH = 4.8/4.8) and Happy Valley (IP/P: pH = 4.5/5.0). Soil exchangeable calcium followed a similar pattern to pH across the NAAT. Calcium was lower at the northernmost three sites and ranged from 2293/1803 mg kg^{-1} (IP/P) at Isachsen to 6523/2430 mg kg^{-1} (IP/P) at the Mould Bay site, with low Ca also at the two southernmost acidic pH sites of Sagwon-at and Happy Valley, 1802/1003 mg kg^{-1} and 4157/641 mg kg^{-1} (IP/P) respectively. Exchangeable sodium was generally low (ranging from 7 to 41 mg kg^{-1}) except at the locations of Howe Island, Deadhorse, and Green Cabin. High levels of Na were in the pattern soils of Green Cabin and Howe Island, 92 and 532 mg kg^{-1} respectively, and in the interpattern of Deadhorse at 217 mg kg^{-1}. Extractable macronutrients nitrogen, phosphorus and potassium were at highest levels in the interpattern soils of the Isachsen, Mould Bay, Deadhorse and Happy Valley sites ranging from 6 to 11 mgN kg^{-1}, 8 to 32 mgP kg^{-1}, and 220 to 586 mgK kg^{-1}. The macronutrients at the other sites were lower ranging from 1 to 4 mgN kg^{-1}, <1 to 5 mgP kg^{-1}, and 27 to 197 mgK kg^{-1}.

[12] Total organic carbon (%OC) and soil carbon to nitrogen ratios (C:N) are given in Figure 4. With the notable exception of the IP soils from Mould Bay and Deadhorse (22.8 and 24.1%OC) surface OC remains low from Isachsen in the north to Franklin Bluffs in the south ranging from 1.5 to 5.5%OC. Surface soil %OC of the IP position increases going south from Franklin Bluffs to Happy Valley rising from 5.5 to 27.0%OC while pattern OC remains lower at 1.5

to 3.8%OC. Carbon quality as indicated by the soil C:N ranges from 13 to 36 in the Sagwon-nt and Deadhorse sites respectively, and from 14 to 34 in the Isachsen and Happy Valley sites respectively. The Deadhorse site had the highest volumetric water content with 77% and 52% for the IP and P soils respectively. The other sites had water contents ranging from 19 to 50%.

4. Discussion

4.1. Whole Soil Profiles

[13] With the exception of the northernmost location soils were of a medium or loamy texture with few coarse fragments. These are the types of soil materials that lend themselves to the formation of circle patterned ground features as medium texture materials are necessary for initial pattern development [*Peterson and Krantz*, 2003]. This is consistent with the observation of only cracking patterns and polygons with no circles observed at the northernmost Isachsen site having clay soils. In Arctic regions there is little clay mineral formation due to cold-temperatures and weak mineral weathering activity compared to temperate and tropical regions [*Ping et al.*, 1998; *Borden*, 2005]. This makes it likely that the textures of NAAT soils are largely inherited from disintegration of local geologic materials at all the locations. In the north, the clays of Isachsen are from disintegrating shales [*Foscolos and Kodama*, 1981], sandy loams of Mould Bay from the local sand and siltstones [*Everett*, 1968], and the sandy loams of Green Cabin from the sandstone, siltstones and marine deposits at depth. The active layer soils for the Alaska coastal plain locations are formed in the silty carbonate-laden aeolian and fluvial deposits: Howe Is., Deadhorse, and Franklin Bluff locations [*Everett*, 1975]. Aeolian silts make up the active layer for the Sagwon-nt and Sagwon-at locations [*Walker and Everett*, 1991]. The heavier textured (silty clay loam) soils in Happy Valley formed in glacial till mixed with only smaller amounts of loess [*Borden*, 2005].

[14] Soil pH and soluble salt levels also generally follow the geologic character inherited from parent materials for each NAAT location (Figure 2). Acidic active layer conditions and lower soluble salt (EC) levels were found for Isachsen in the far north and Sagwon-at and Happy Valley in the far south. In the north at Isachsen acidic conditions are more inherited from the geologic formation there as there is slower and less soil formation and accumulation of OC that is acid producing along with lower precipitation compared to the southernmost sites. With the accumulation and degradation of organic matter highest and temperatures highest at the southern locations comes increased production of soil acidity promoting cation removal and replacement with protons on the soil exchange complex [*Ping et al.*, 2005]. This is consistent with a generally lower level of weathering release of soil ions in the north and acidification and removal of ions in the south with higher soil solution ions in the nonacidic locations in between.

[15] In general both soil OC and N concentrations increase moving south along the biogradient, as soil bulk density (BD, Figure 2) decreases. However, soil texture and pH did not follow the general pattern of increasing north to south probably because they were more closely associated with soil parent material as opposed to being strongly bioclimate related. Soil soluble salts were intermediate in that they follow ions of parent materials (Ca, Mg, and Na) available at the location but their distributions were affected by local (topographic) and bioclimatic gradient conditions. Conditions such as evaporation and water transport resulted in disproportional accumulation in the soils of Mould Bay and Howe Island where conditions were dry and sources of ions high. Soil TOC, N and BD followed a north south gradient due largely to increasingly favorable bioclimatic conditions reflected in concurrent north to south biomass increases [*Raynolds et al.*, 2008].

[16] Figure 3 presents schematic representations of soils of frost boil cross sections (interpattern/pattern area of soil profiles of NAAT zonal vegetation sites to 1 m depth). Key soil parameter data under the pattern ground can be partitioned into separate but interacting zones: the active-layer interpattern, active-layer pattern and the permafrost (to 1 m depth). Each of the zones function to maintain the pattern [*Peterson and Krantz*, 2003] with the active-layer-pattern and interpattern zones providing water to form ice lenses. Ice lens formation in turn results in differential frost heave with the permafrost providing a constant heat sink and physical restriction to soil and water downward movement. Thickness of the active layer as well as the difference between interpattern and pattern areas increases from Isachsen in the north to Franklin Bluffs in the south, then decrease in the Alaska foothills locations of Sagwon-nt, Sagwon-at and Happy Valley. The thicker active layers of the midtransect locations have been similarly noted by many studies attributing the trend to the warmer temperatures moving southward interacting with the increased insulating effects of thickening surface vegetation mats and surface organic soil horizons in the far south [*Romanovsky et al.*, 2003; *Nelson et al.*, 1997]. In the far south biotic factors associated with surface organic matter accumulation to insulate the soil surface exerts control limiting heat transfer to the soil and thus begins controlling thaw-depth. The increased vegetation layer thicknesses are reflected in biomass data (Figure 3) increasing from 17 kg 100 m^{-2} in the north to 75 kg 100 m^{-2} in the south (data from *Raynolds et al.* [2008]). Water content in the soil is unevenly distributed at most locations often with large differences between the active-layer and the permafrost. Water content for the upper permafrost table shown here can vary widely within meters due to the presence or absence of massive ice as ice wedges and ground ice or ataxitic layers (soil suspended in ice matrix) encountered in the intermediate zone of the upper permafrost [*Shur*, 1988; *Ping et al.*, 2008]. Water content of the active-layer tended to increase from north to south with the exception of Isachsen being 30–36% water by volume due to the higher water holding capacity of the clay soils relative to the loamy soils found throughout the southern NAAT locations. However, water held in these fine clay textured soils is largely in micropores and not available for easy transfer within the soil that is necessary to build ice lenses and produce larger amounts of heave [*Peterson and Krantz*, 2003]. The water content of the interpattern area was not consistently higher than the pattern area as might be expected but there was sufficient water in each location to support the heave measured at the locations [*Walker et al.*, 2008], for most there was enough even without the cryosuction transfer of water from the interpattern area to the pattern during

freezeup [*Peterson and Krantz*, 2003]. The partitioning of organic carbon (OC) was also variable along the NAAT with some locations having higher interpattern OC while others had higher OC in the pattern. This was dependant on the presence or absence of organic enhanced A-horizons and cryotubated O/B or A/B combination horizons, as these horizons contained significant amounts of OC [*Michaelson et al.*, 1996; *Bockheim et al.*, 1998] for soils of the south and north locations (see Table S1). The most apparent trend other than the general increase in profile OC from north to south is the increase in amount of OC sequestered in permafrost. The exception was at the Sagwon-nt location and could be due to its ridge top location and relatively deep active layer.

4.2. Surface Soil

[17] Soil surface properties and conditions are especially important to patterned ground ecosystems as they support the biological/vegetation component of the system. This is the component of the systems that exerts strong controls on pattern dynamics [*Kade and Walker*, 2008]. On the more barren pattern areas the soil surface properties are crucial for the establishment of plants and on interpattern areas they can determine plant community development [*Walker et al.*, 2004]. In particular surface soil pH (Figure 4) varied in a manner consistent with the average pH of the whole profile (Figure 2) following the same pattern of rise and fall from north to south.

[18] There were interesting environmental interactions for the cations sodium, potassium and calcium in the IP/P areas at Green Cabin, Howe Island and Deadhorse (Figure 4). The source of sodium was marine shale at Green Cabin and for Howe Island and Deadhorse sites close proximity to the Arctic Ocean. The water content of the surface soil at Deadhorse was distinctly higher than at Green Cabin and Howe Island (Figure 4). Sodium levels for the drier two locations tended to be highest in the pattern (very high for Howe Island) whereas at the wetter Deadhorse location sodium and calcium were higher in the interpattern. This would suggest that evaporative loss in the bare surface pattern areas of drier locations tends to transfer and concentrate sodium in pattern centers. This transfer/concentration process happened only where sodium was present in larger amounts and where there were dryer conditions. A distinct ground patterning observed at the Howe Island location relative to other surrounding areas [*Walker et al.*, 2008] could be largely as a result of this surface salt segregation phenomena interacting with vegetation establishment. Although potassium tended to be higher in interpattern areas across the NAAT, the only location where it was higher in the pattern was Banks Island. This could be a result of evaporative transfer/deposition also with lower competing levels of sodium compared to Howe Island. Soil calcium tended to be higher in the interpattern relative to the pattern area at most locations across the NAAT. This was consistent with the higher cation exchange capacity (CEC) found for interpattern areas relative to pattern areas across the NAAT due to the CEC being highly dependent on soil organic matter and not clay content ($R^2 = 0.90$, $p < 0.01$, for the relationship of CEC with percentage OC data not shown). This is consistent with the relationship found by *Ping et al.* [2005] for soils across the Alaskan Arctic.

[19] All locations tended to have higher P levels in the interpattern relative to the pattern (Figure 4). This is consistent with bioaccumulation and cycling within the organic matter. Phosphorus and N across all locations was correlated to OC content ($R^2 = 0.72$, $p < 0.01$ and 0.53, $p < 0.01$ respectively). Locations with lower overall OC levels tended to have smaller or no differences in available-N between interpattern and pattern (Isachsen, Green Cabin, Howe Island, and Franklin Bluffs). Soil potassium levels followed a similar pattern to P and were also correlated to percentage OC ($R^2 = 0.68$, $p < 0.01$).

[20] Soil C:N ratios for both the interpattern and pattern followed similar up and down trends across the NAAT (Figure 4). The similarity in IP/P variation across the sites reflects the overall effects of biomass quality that is inherited from vegetation community differences combined with the nature and extent of decomposition across the sites. The decomposition is affected by many environmental factors including temperature and moisture interacting with litter quality [*Hobbie et al.*, 2000]. For sites on the North Slope of Alaska (Deadhorse south to Happy Valley) trends in C:N mirrored %OC in the soil, high for Deadhorse then low and increasing to Happy Valley in the south. The higher water content for the Deadhorse site could contribute to OC preservation there. The low to high relationship of C:N between the coastal plain and the foothills has been noted for the Alaska North Slope by others [*Ping et al.*, 1998] and attributed to lower quality high lignin contents for foothills acidic tundra plant communities relative to the more herbaceous nonacidic tundra to the north [*Hobbie et al.*, 2000]. For the individual sites C:N ratio differences between IP/P reflects differing quality of organic matter. The C:N ratios of the pattern area surface soils also could reflect large differences in composition of the vegetation and biotic communities between IP/P. These differences in combination with the generally warmer-dryer conditions existing in the pattern area could favor decomposition there relative to the interpattern areas [*Walker et al.*, 2004; *Kade and Walker*, 2008]. Ratios tended to be lower in the pattern area relative to the interpattern areas for 6 of the 9 sites. It is notable that there is not a consistent trend for all sites. Without further investigation into the character of the organic matter which is very heterogeneous it is difficult to evaluate quality based on C:N ratios alone [*Xu*, 2005].

4.3. Soil Properties and Patterned Ground

[21] Combining the ideas of *Peterson and Krantz* [2003] and *Walker et al.* [2004], Figure 5 presents a simplified conceptual framework for some of the main relationships between physical, biological and chemical parameters important for functioning of the pattern ground system. General causality of the factors for pattern structure development, maintenance and some of their interactions (as displayed in Figure 5) have been demonstrated in laboratory experiments [*Peterson and Krantz*, 2003], field manipulations [*Kade and Walker*, 2008] and in overall evaluations of the complex systems [*Walker et al.*, 2004]. We present the conceptual diagram with simple correlations using measured soils data for the sole purpose of testing consistency of the concept to the data collected over the broader set of Arctic conditions on the NAAT. Measured field data of this scale has not been evaluated or been

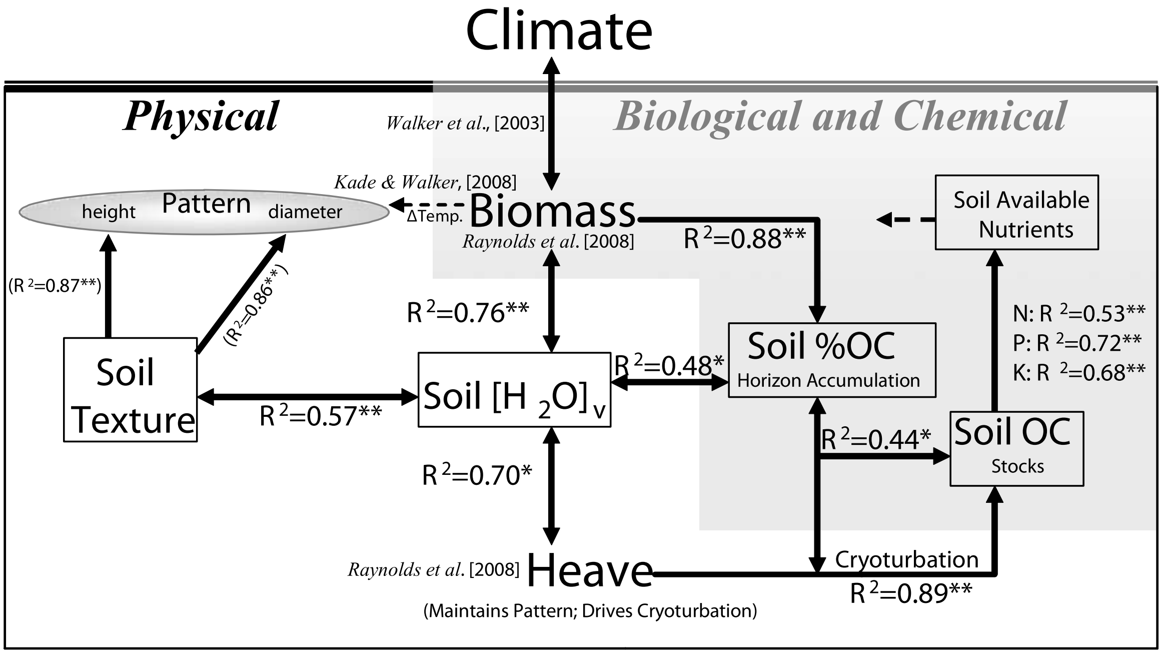

Figure 5. A simplified conceptual diagram for some of the main relationships between soil parameters that were measured in this study (shown in boxes) with biomass and heave from *Raynolds et al.* [2008], all data from the NAAT zonal vegetation locations. The R^2-values (significance: ** = $p < 0.01$, * = $p < 0.05$) given were for linear regressions among data.

available until now. Soil parameters measured in this study are shown in boxes. Other parameter from the same study sites are biomass taken from *Raynolds et al.* [2008] and heave from *Walker et al.* [2008]. Climate over the bioclimatic gradient has an obvious effect on biomass as discussed by *Walker et al.* [2005, 2008], *Raynolds et al.* [2008] as well as others.

[22] Across the sites, water content of the active layer under the pattern (data: Figure 3) was well correlated to biomass (Figure 5, R^2 = 0.76, $p < 0.01$) and to a lesser degree with horizon accumulation of OC (Figure 5, R^2 = 0.48, $p < 0.05$). Soil water and biomass production are linked naturally as water is necessary for and often limiting plant growth. For the zonal vegetation sites across the NAAT, biomass, temperature and precipitation increase from north to south [*Raynolds et al.*, 2008; *Walker et al.*, 2005]. Soil texture is also linked to soil water content (R^2 = 0.57, $p < 0.01$) across the loamy textured soils of the NAAT, this is likely due to the fact that finer textured soil (higher clay content) can hold larger volumetric water contents compared to coarser (more sandy) soils [*Brady and Weil*, 1999]. Soil water in the pattern area is related to frost heave directly (R^2 = 0.70, $p < 0.1$ Figure 5). Frost heave is strongly controlled not just by available water but rate or progression of freezing in the fall and early winter [*Peterson and Krantz*, 2003]. Frost heave works to influence pattern expression or morphology (height and diameter, Figure 5). Six pattern soils examined at the Mould Bay location (data not shown) had a range of silt content from 20 to 36% and pattern diameters from 20 to 130 cm with pattern center heights from 2 to 20 cm in relief. Within this location there were good relationships between silt content and pattern height (R^2 = 0.87, $p < 0.01$) and silt content and pattern diameter (R^2 = 0.86, $p < 0.01$). This is consistent with the fine fractions of silt being most susceptible to frost action and receptive to heave given sufficient water content to form ice lenses [*Peterson and Krantz*, 2003].

[23] A strong relationship was observed between the amount of frost heave and soil OC stocks under the pattern of the active layer (Figure 5, R^2 = 0.89, $p < 0.01$). This is consistent with and supports the theorized link between frost heave and the cryoturbation process. Previously this link is supported only by soil morphology observations [*Bockheim et al.*, 1998]. The simple correlations made with this data do not reflect the complete matrix of possible factors, interactions and synergies as soil organic matter increases could increase the amount of soil water available to support heave and thus add to the overall relationship between frost heave and soil OC stocks. These data are quite possibly the first direct data supporting this link, to be reported in the literature even as cryoturbation is so prevalent in Gelisols found across the Arctic. Also active in the system are direct processes of OC accumulation into the soil with organic horizon build-up, root die-off and the subsequent formation of soil A-horizons. This is evidenced by a strong link between biomass and horizon accumulation of OC by weight or average %OC of soil profile horizons (Figure 5, R^2 = 0.88, $p < 0.01$). The morphology in these soils shows that much of this accumulated OC in horizons is over time moved to the lower active layer by cryoturbation [*Michaelson et al.*, 1996; *Bockheim et al.*, 1998; *Ping et al.*, 1998]. The direct association between horizon accumulation of %OC and soil OC stocks is weaker but significant (Figure 5; R^2 = 0.44, $p < 0.05$). There was no significant direct relationship between biomass and soil OC stocks (R^2 = 0.25, ns). The stronger link between soil OC stocks and biomass could be through nutrients released as soil OC builds up and decomposes which increases soil nutrient

pools but not necessarily soil fertility. The nutrient-biomass link could be strong within a site (data not shown here), but this would be overshadowed by soil parent material causing greater magnitude of nutrient differences across the NAAT locations (example: soil extractable P levels, Figure 4). Utilization of nutrients to create more biomass will likely be dependant on many other environmental factors affecting fertility as temperature, hydrology and plant community responses. For these NAAT locations though a positive relationship was observed between each of the plant macro-nutrients nitrogen, phosphorus and potassium in the surface 0–5 cm of the soil active-layer and the amount of soil OC stocks in this 5 cm layer (Figure 5: $R^2 = 0.53$, 0.72 and 0.68 respectively, all $p < 0.01$). This is consistent with the findings of other studies where bioaccumulation has a very strong influence on nutrient availability for tundra soils of Alaska [*Broll et al.*, 1999; *Michaelson et al.*, 2002].

5. Conclusions

[24] Soil parent materials vary considerably across the Arctic and exert a strong influence on key soil properties especially soil texture, pH, EC, and on nutrient levels such as phosphorus, sodium and calcium. It is known that pH controls plant community composition but high salt parent materials with drying climate conditions can exert similar controls through nutrient segregation and concentration across the surface of frost boils. These processes can affect both vegetation and pattern expression in frost boils. Vegetative cover (insulation) has been found by others to be crucial to frost boil dynamics and expression. Our results illustrate the dynamic-complex nature of the interaction between the physical (parent materials and climate conditions) and chemical (salt species and concentration) aspects of the system in supporting or limiting the biological-vegetation influences. This interaction can occur across gradients in bioclimate suggesting that influences of parent materials will be strong even as climate changes progress. Fundamental soil properties especially soil pH and salinity will exert some control over frost boil dynamics through there controls on vegetation and soil fertility. These controls are a significant part of the system complexity and could overshadow those of simple climate gradient changes for certain arctic regions.

[25] Nutrients essential to plant growth and establishment are related to biological build-up and storage of OC in frost boil soils. Since plant vigor depends in part on soil nutrient availability, the build-up of OC in soil is one of the key factors in addition to parent materials controls for vegetation community development on frost boil systems. In turn physical dynamics of the pattern will effect OC sequestration (and nutrient pools and distribution of pools) primarily through cryoturbation in active systems and through cumulative surface build-up of OC as frost boil dynamics subside.

[26] Soil properties related well to important elements of the frost boil system across the NAAT showing good agreement with the model concepts for frost boil dynamics put forth by others [*Peterson and Krantz*, 2003; *Walker et al.*, 2004]. Across the bioclimatic gradient there are reasonably good simple correlations between biomass-soil water and soil texture-soil water and for soil water with heave measurements. These results support the presence of good biological to physical linkages in the system across a variety of parent materials and soils on the NAAT. Perhaps the strongest and most interesting relationship having biological consequences was found for heave and soil OC stocks in the active layer under the pattern areas. This is a relationship of particular interest because it relates heave and cryoturbation both of which link to biomass and OC sequestration. These are central components in assessing affects of climate change on OC dynamics. This biological-physical-chemical linkage has been theorized but to the best of our knowledge has not been measured before across the Arctic environment. The importance of this is that it supports links between measured soil properties and elements of the physical and biological factors affecting OC sequestration and cycling. These links however, need to be put in the context of other influential factors and further quantified in order to build a functional model that is useful in the assessment of climate change affects across the Arctic. These field data from across the Arctic are a first step to better understanding and quantifying the simple relationships that make up a larger matrix of component factors determining frost boil characteristics, dynamics and carbon sequestration.

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