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Relationship of Permafrost Cryofacies to Varying Surface and Subsurface Terrain Conditions in the Brooks Range and foothills of Northern Alaska, USA

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Abstract

Permafrost landscape responses to climate change and disturbance impact local ecology and global greenhouse gas concentrations, but the nature and magnitude of response is linked with vegetation, terrain and permafrost properties that vary markedly across landscapes. As a subsurface property, permafrost conditions are difficult to characterize across landscapes, and modelled estimates rely upon relationships among permafrost characteristics and surface properties. While a general relationship among landscape and permafrost properties has been recognized throughout the Arctic, the nature of these relationships is poorly documented in many regions, limiting modelling capability. We examined relationships among terrain, vegetation and permafrost within the Brooks Range and foothills of northern Alaska using field data from diverse sites and multiple factor analysis ordination. Terrain, vegetation and permafrost conditions were correlated throughout the region, with field sites falling into four statistically-separable groups based on ordination results. Our results identify index variables for honing field sampling and statistical analysis, illustrate the nature of relationships in the region, support future modelling of permafrost properties, and suggest a state factor approach for organizing data and ideas relevant for modelling of permafrost properties at a regional scale.

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1. Introduction

Permafrost landscapes are critical components of global climate change, but responses and feedbacks depend on ecosystem properties, which vary markedly throughout the Arctic. Permafrost landscape structure develops through a complex interplay among climate, substrate, and surficial processes operating at multiple spatial and temporal scales (Shur and Jorgenson 2007). At the interface between the atmosphere and deep permafrost, processes of vegetation, soil, and upper-permafrost cryostructures respond to climate shifts and disturbance (Viereck 1973, ACIA 2005, Jorgenson et al. 2010a, Jorgenson et al. 2013), and mediate the influence of climate on deeper permafrost (Shur and Jorgenson 2007, French and Shur 2010). Vegetation and upper permafrost horizon development have been linked with terrain properties and climate (Kreig and Reger 1982, Shur 1988, Shur and Jorgenson 2007, Pastick et al. 2014), and are mutually influential at local and circumarctic scales, though the nature and extent of relationships among vegetation and permafrost is only partially understood (Raynolds and Walker 2008, Walker et al. 2008, French and Shur 2010, Lantz et al. 2010, Kokelj and Jorgenson 2013).

In the Brooks Range and foothills of northern Alaska, multiple modes of permafrost degradation appear to be accelerating (Jorgenson et al. 2006, Bowden et al. 2008, Jorgenson et al. 2008a, Balser et al. 2009, Gooseff et al. 2009), but relationships among terrain properties, vegetation, and upper permafrost characteristics are weakly documented (Jorgenson et al. 2008a, Jorgenson et al. 2010b). Region-wide estimates of future landscape resilience and response to climate perturbation depend on spatially-explicit representations of permafrost conditions (Callaghan et al. 2004), but subsurface permafrost properties across the landscape are difficult to observe directly. Determination of permafrost properties in remote, northern Alaska depends on understanding relationships among terrain, vegetation and permafrost, and applying them at a

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regional scale. Determining which specific terrain properties and groups of terrain properties are most correlated with vegetation and upper permafrost conditions within this region, and the degree to which correlations apply across diverse landscapes, is central to future estimates of resilience, responses, and feedbacks to climate in the Brooks Range and foothills of northern Alaska.

1.1 Responses and feedbacks to climate

Permafrost degradation rate has been increasing in recent decades throughout the circumarctic and is anticipated to continue or accelerate (ACIA 2005, Hinzman et al. 2005, Schuur and Abbott 2011). Marked impacts and feedbacks are expected across the cryosphere, with shifts in ecosystem structure and function (Callaghan et al. 2004, Osterkamp et al. 2009, Goetz et al. 2011, Myers-Smith et al. 2011), local and global hydrologic cycles (Peterson et al. 2002, Hinzman et al. 2006, Frey et al. 2007), and biogeochemistry and carbon release (Tarnocai et al. 2009, Grosse et al. 2011, Schaefer et al. 2011).

Distinct modes of permafrost degradation correlate with specific combinations of surficial landscape properties, each with a different influence on ecological, hydrological, and biogeochemical shifts, and characterized by distinct morphologies and processes (Hinzman et al. 2005, Jorgenson and Osterkamp 2005, Schuur et al. 2009, Lafreniere and Lamoureux 2013). Modes of permafrost degradation include active-layer deepening, as well as an array of subsidence features broadly termed 'thermokarst' (Hinzman et al. 2005, Jorgenson et al. 2008a). Each mode affects ecosystem properties and processes at different depths, rates, and scales, in turn driving the nature and magnitude of overall impacts (Jorgenson et al. 2013). Modes of permafrost degradation in response to climate perturbation or disturbance are coupled with local surficial conditions, including thermal properties, thaw stability, slope, hydrology and ground ice

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characteristics (Leibman et al. 2003, Lewkowicz and Harris 2005, Jorgenson et al. 2008a, Kokelj et al. 2009, Jorgenson et al. 2010a, Lantuit et al. 2012). Thermal properties, thaw stability, and hydrology, in turn, are influenced by cryostructure distribution and ground ice content, vegetation, and soil composition and organic layer development (Shur and Jorgenson 2007) .

1.2 Landscape variability

Vegetation development on the surface and cryostructure development in the upper-permafrost are dynamically linked ecosystem processes organized in complex but potentially generalizable patterns across landscapes. Mutual influences between vegetation and permafrost (Raynolds and Walker 2008) are linked with terrain characteristics, surficial thermal properties, and hydrology (Shur and Jorgenson 2007, French and Shur 2010). These may be considered within the 'state factor' framework, which groups terrain properties within five umbrella categories: biota, parent material, topography, climate, and time (Jenny 1941, van Cleve et al. 1991, Jorgenson et al. 2013).

On newly deposited surfaces, topography, surficial geology, climate, and potential recruitment drive initial development of vegetation and new cryostructures, and influence the fate of pre-existing ground ice, such as relict glacial ice (Washburn 1980, Shur 1988, Walker et al. 2008, French and Shur 2010). With time, vegetation and cryostructure development exert increasing influence at the surface, mediating heat flux, soil moisture, and decomposition rate of organic matter, which in turn feeds back on vegetation and cryostructure development (Davis 2001, Hobbie and Gough 2004, Walker et al. 2008). Vegetation, active-layer depth, and the nature and degree of permafrost and cryostructure development across heterogeneous landscapes are a product of these interactions (Shur and Jorgenson 2007, Raynolds and Walker 2008, Walker et al. 2008, French and Shur 2010, Walker et al. 2011). Correlations among vegetation

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and permafrost characteristics are recognized from studies at specific sites (Kreig and Reger 1982, Shur and Jorgenson 2007, Walker et al. 2008, Kanevskiy et al. 2011, Epstein et al. 2012), and from regional to circumarctic-scale studies (Raynolds and Walker 2008, Gruber 2012, Pastick et al. 2014).

1.3 Integrating terrain properties

A general approach describing relationships among terrain properties and permafrost, congruent with the state factor framework (Shur and Jorgenson 2007), has been developed to better estimate permafrost vulnerability among different landscapes. Terrain properties and permafrost characteristics co-vary, and consistency of associations among permafrost, terrain and vegetation enable landscape-scale analysis on that basis (Jorgenson and Kreig 1988, Raynolds and Walker 2008, Jorgenson et al. 2010a, Jorgenson et al. 2013, Pastick et al. 2014). While the importance of surficial deposits (Kreig and Reger 1982, Jorgenson et al. 2008a) and vegetation (Viereck 1973) to ground ice and permafrost development have long been recognized, landscape-scale methods for integrating terrain factors are not fully developed. Toward improved terrain factor integration, we hypothesized that: 1) vegetation and permafrost properties consistently correlate with specific terrain conditions across landscapes due to these relationships; 2) that diverse landscapes may fall into general groupings from statistical analysis of empirical field data for these combined properties; and 3) that these relationships can be used to help identify which terrain factors, in combination, facilitate spatial characterization of surficial landscape properties in the Brooks Range and foothills of northern Alaska.

Our research tested these ideas statistically using ordination of field survey data collected from sites representing diverse landscapes in the Brooks Range and foothills of northern Alaska. Identifying statistically-supported linkages between permafrost properties (ground ice content

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and cryostructures), and terrain properties (vegetation and surficial geology), can facilitate regional scale estimation of permafrost vulnerability and estimation of ground ice conditions, and better inform models examining regional resilience, response and feedbacks to climate change.

2. Methods

2.1. Study region

Our research spanned a gradient of arctic tundra including barren, herbaceous, and shrub landscapes within Alaska's Brooks Range and foothills, from the east-central portion of Alaska's North Slope westward through the Noatak Basin to the Mission Lowlands, near the Noatak delta (Figure 1). These periglacial landscapes are within the continuous permafrost zone (Jorgenson et al. 2008b) and are part of Arctic Bioclimate Subzone E (CAVM-Team 2003). The northeast portion of the study region was centered around Toolik Field Station on the north slope of Alaska, while the central and western study region followed the Noatak Basin from near its headwaters downstream to the Mission Lowlands, near the Noatak River delta.

Toolik Field Station is located in the northern Brooks Range foothills within a mosaic of landscapes of varying glacial ages and ecotypes. Physiography ranges from low mountains at the edge of the Brooks Range to subtle foothills stretching more than 75 km from the mountains to the edge of the Arctic Coastal Plain. Date since most recent glaciation ranges from early Pleistocene to Holocene for field sites surrounding Toolik Field Station, with acidic and nonacidic, graminoid and shrub tundra vegetation reflecting duration of ecosystem development and local site conditions (Walker et al. 1994, Walker et al. 1995, Hamilton 2003, Walker and

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Maier 2008). Lake and stream density is variable by landscape age-class and related with glacial and periglacial landforms (Hobbie et al. 1991, Kling 1995, Hamilton 2003).

The Noatak River flows 730 km along a westward course at approximately 67.5° N (Figure 1). Most of the 33,100-km^2 basin falls within the Noatak National Preserve (U.S. National Park Service) and is recognized as a UNESCO Biosphere Reserve. The Noatak Basin was periodically glaciated throughout the Pleistocene and contains a patchwork of glacial and periglacial landforms ranging in age from early Pleistocene to contemporary (Hamilton 2010, Hamilton and Labay 2011). Physiographic provinces include high mountains of the east-central Brooks Range, through foothills and valley bottoms to the Mission Lowlands at the arctic-boreal ecotone near the Noatak mouth (Wahrhaftig 1965, Young 1974). Land cover spans a gradient of vegetation and ecotypes including arctic and alpine tundra, shrublands and lowland boreal forest (Young 1974, Viereck et al. 1992, Parker 2006, Jorgenson et al. 2010b).

Landscape conditions throughout this 500-km-wide region represent a broad range of typical low-arctic landscapes (Figure 2). Alpine, foothill, and valley bottom settings include many characteristic ecotypes of the North American Low Arctic, a suite of periglacial landforms, diverse surficial geology and lithology, and a broad continuum of permafrost characteristics and cryostructures. While a geographic gap exists between the Toolik and Noatak subregions, substantial overlap among terrain properties and permafrost cryostratigraphy link them conceptually. Our study deliberately included a wide range of conditions over a large geographic area to represent a diversity of low-arctic landscapes in the region.

2.2 Field surveys

Our regional surveys identified areas of surface-exposed and degrading permafrost distributed among diverse landscapes, from which we selected field sites representing a range of low-arctic conditions. Aircraft-supported field campaigns and airphoto analysis in 2006, 2007, and 2008 were used to identify watersheds with actively degrading permafrost exposures representing different modes of degradation (and by proxy, differing ground-ice conditions). Several thousand permafrost degradation feature locations were recorded in an ArcGIS GeoDatabase, which was later expanded and augmented through a subsequent National Park Service survey, which included both Gates of the Arctic National Park and Preserve and Noatak National Preserve, using high-resolution satellite imagery to census these features throughout both park units (Balser et al. 2009, Swanson and Hill 2010). These data drove spatial analyses identifying diverse combinations of ecotype, lithology and surficial geology among subwatersheds accessible by helicopter from field camps at Kelly River, Feniak Lake, and Toolik Field Station (Figure 1). During subsequent helicopter-based visits in 2009, 2010, and 2011, field sites were chosen for detailed examination based on: 1) best accessibility to exposures of permafrost; and 2) inclusive representation among terrain properties including ecotype, lithology, and surficial geology.

At each of 54 field sites, we measured and described general landscape characteristics and specific conditions at the site of permafrost exposure. A subset of categorical and quantitative data collection protocols and field codes were adopted from Jorgenson et al. (2010b) to characterize ambient surface properties (within approximately 100 m of the permafrost exposure) and to catalog the specific combination of vegetation, soil, surficial geology and cryostratigraphy immediately at the site of permafrost exposure (Table 1). Basic geomorphology, lithology, surficial geology, topography, and landforms were recorded to represent the area within

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approximately 100 m of the permafrost exposure. Vegetation was recorded both by class (Viereck et al. 1992) and as a list of predominant overstory and understory species of vascular plants, and functional groups of bryophytes within 20 m of the permafrost exposure.

Permafrost profile exposures were described in detail to characterize and quantify properties of the live vegetative mat, contemporary soil (organic and mineral), parent material and archaic soils, coarse fraction, ice content, cryostratigraphy, and interpretations of mechanisms of cryogenesis. Permafrost exposures were predominantly composed of vertical scarps at actively degrading edges of retrogressive thaw slumps, active layer detachment slides and thermo-erosional gullies (Figure 3). Permafrost exposures were prepared using hand tools to remove previously thawed material and expose an intact permafrost profile from the top (ground surface) down to the greatest accessible depth within the thaw feature (Figure 4). Exposures were prepared to a width of at least 1 m, with categorical and quantitative tabular data taken for each discernible layer in the profile (Figure 4) from vegetation at the surface to the bottom of the exposure. Data from each discernible subsurface layer were weighted by layer thickness and integrated to generate overall values for: 1) contemporary soil; and 2) archaic soil layers and parent material (Table 2). Hand-drawn cryostratigraphic maps roughly following Kanevskiy et al. (2011), and detail photos for each permafrost profile complement data and general site photos and were used for interpretation and summarization.

2.3 Data analysis

2.3.1 Data reduction

To statistically analyze data from our 46 field sites by terrain and permafrost properties, we began with data reduction to eliminate extraneous independent variables with minimal contribution to our model and to reduce redundancy in the data. We employed Pearson (r) correlations in two separate steps to examine redundancy and to identify variables with minimal contribution to ordination results. In the first step, a Pearson correlation analysis of all variables against one another with R statistical software was used to examine inter-variable relationships and identify groups of variables that might be represented by a single integrator variable. Where a set of variables was grouped by Pearson scores > 0.60 for all pairings, the group was considered a candidate for integration.

In the second step, all variables went through a pilot, three-axis non-metric multidimensional scaling (NMS) ordination with 50 runs of 250 iterations in PC-ORD to generate Pearson correlation values for each variable against each ordination axis. This ordination was used to examine the contribution of each variable to the ordination and eliminate those with minimal analytical value. For this analysis, categorical data were transformed to binary numbers for each categorical unit of each categorical variable, while continuous and ordinal data were scaled 0 to 1 (precision to the hundredth) to conform with NMS analysis assumptions for a valid distance matrix (McCune and Grace 2002, McCune 2013). Those variables with NMS Pearson scores < 0.30 for each axis were deemed extraneous and excluded from subsequent ordination. From each grouping of highly correlated variables identified in step one, a single integrator variable was chosen from the group based on highest cumulative Pearson score across all axes in step two.

2.3.2 Multiple factor analysis ordination

Relationships among permafrost and terrain properties were examined using multiple factor analysis (MFA) ordination of 46 surveyed field sites. Traditional ordination is conducted on datasets where all variables are comparable and of the same type (e.g., vegetative species by percent cover). While the goals of our analysis were similar to outcomes derived from

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traditional ordination (e.g., site similarity and clustering in multidimensional space as determined by a distance matrix), our dataset comprised different logical groupings of data for each site (e.g., ice, substrate and vegetation) and dissimilar data types, such as coarse fragment size class (ordinal), vegetation type (categorical), and ice percentage (continuous).

MFA, a recent adaptation of principal component analysis (PCA), was chosen for this application of ordination because it is designed to integrate dissimilar data types and different logical groupings of data (termed 'blocks') for each observation within a single ordination run (Escofier and Pagès 1994). While other ordination techniques, such as NMS, can also be applied after data transformation and scaling (McCune and Grace 2002, McCune 2013), MFA offers two distinct advantages over NMS and other ordination techniques under these conditions. First, end-user data transformation is unnecessary because MFA performs data normalization in an initial PCA step, using the square root of the first eigenvalue in a manner comparable to Z-score normalization (Abdi et al. 2013). These normalized data are then merged to form the analysis matrix, enabling valid distance matrices to be calculated from what were initially incongruous variables. Second, MFA provides the option to define blocks of data, which are conceptually coherent groups of variables pertaining to all observations (Abdi et al. 2013). The chief advantage of a block approach is that individual blocks of data (e.g., vegetation, substrate, ice) are inhibited from dominating the ordination results while other blocks become de-emphasized. MFA achieves this parity by normalizing the input data by block, and by handling each block as a sub-matrix of the whole. The first principal component of each block is scaled to 1 in the normalization step, which ensures that no block will dominate the model through disproportionate inertia in the final ordination (Abdi et al. 2013). Finally, each block must

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contain variables of the same data type for the normalization step to produce valid results. Thus, conceptual blocks containing multiple data types were split by type.

Data were originally recorded by segment of the study site (Tables 1 and 2), but were reorganized for statistical analysis into response variables and independent variables, and by block. To effectively address the hypothesis that terrain properties consistently influence cryostructure, ground ice, and vegetation across sites, we divided the dataset into response variables and independent variables from the perspective of the current ecosystem. Site characteristics that predate and may potentially influence the current ecosystem (e.g., surficial geology) were classed as independent variables, while properties influenced by contemporary ecosystem processes (e.g., vegetation, microtopography and upper permafrost cryostructures) were classed as response variables and assigned to blocks. Response variables, termed 'active' variables in MFA, were the basis of ordination calculations. Potential explanatory or 'supplemental' variables were employed as overlays on graphs of analysis results to illustrate underlying drivers of statistically demonstrated relationships among permafrost, substrate and vegetation. The final set of variables, selected through Pearson score analyses and reorganized for MFA, were assigned to blocks (Table 3) and ordinated by MFA with three dimensions using the FactoMineR package within R statistical software (Le et al. 2008).

Finally, ordination results were used for hierarchic clustering in FactoMineR to produce a dendrogram depicting relative similarity/dissimilarity among sites, and to delineate statistical groupings of sites. Euclidean distance and Ward's method (0.75 inertia level) were used to generate the dendrogram and delineate groupings (Husson et al. 2010).

3. Results

MFA ordination revealed complex but consistent patterns of correlation among terrain and permafrost properties across sites, and subsequent hierarchical clustering analysis produced four primary groupings, two of which were further divided into subgroups based on subtle but consistent differences among sites. Correspondence among categorical variables within the ordination spanned across different MFA blocks (Figure 5), indicating that factors across the three blocks of vegetative, substrate, and permafrost/ice properties were co-varying among sites. Coarse and fine fraction (substrate), primary permafrost cryostructure (permafrost/ice), and ecotype (vegetative) all contributed to consistent, statistical separation among sites, while specific values for these variables were distributed across sites in complex combinations.

While co-varying, factors organized by block were not redundant in the ordination. Each of the first three ordination axes were driven by differential influences from each block, with axis one driven most by substrate then vegetation, axis two driven most by permafrost/ice then by vegetation, and axis three driven by roughly equivalent influence of all three blocks (Figure 6).

3.1. Hierarchically clustered groupings

Hierarchical clustering of ordination results produced four groupings from 46 sites in the study region (Figure 7). Group E1 contained six sites, E2 comprised 22 sites, E3 had five sites, and group E4 was made up of 13 sites. Groups E2 and E4 were further subdivided, based upon statistical differences driven by identifiable single factors within the ordination. Each group was characterized by combinations of terrain and permafrost properties.

Group E1.

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The E1 grouping was found on late-Pleistocene moraine deposits where: 1) carbonate lithologies comprise more than 10% of clast composition in the substrate; 2) the surface soils were well-drained, nonacidic, and had thin organic layers, and low percentages of massive and segregation ice, and 3) vegetation was dominated by calciphilic species (Table 4 and Figure 9). Substrates were characterized by glacial till overlain by silt, and were generally ice-poor throughout the profile, with low content of massive and segregation ice. Approaching the bottom of profile exposures, glacial till occasionally contained isolated masses of relict glacial ice, and rarely ice-wedges, with combined massive and segregated ice content generally less than 10% by volume throughout the substrate profile. Clasts typically comprised more than 30% of the parent substrate, and often included stone to boulder size rocks (250 - 950 mm). Where proglacial lakes were once present, a mantle of glaciolacustrine deposits occasionally flanked the moraine atop the glacial till with increasing thickness from the moraine crest downward. Thin, post-glacial loess deposits comprised the uppermost substrate, with no evidence of colluvial re-deposition contributing to the profile at any of the sites examined, and minimal buried organic material (3.5% average, by volume). While the active layer was comparatively well drained, the upper permafrost horizon was typically saturated with pore ice. Small lenticular and thin layered cryostructures were usually present, though sparsely dispersed near the top of the permafrost. Total organic-layer depth averaged 7.3 cm and was primarily composed of graminoid detritus.

Vegetation was dominated by upland and alpine graminoid dwarf shrub vegetation, and non-tussock forming sedges and *Dryas integrifolia* dominated all sites. Common calciphilic species included *Oxtropis nigrescens*, and the ericad *Rhododendron lapponicum*. *Eriophorum vaginatum* was present at half of the sites, but occurred at low density lacking tussock

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morphology. Dwarf willow species (primarily *Salix reticulata*), along with *Geum rossii*, *Astragalus umbellatus* and *Pedicularis capitata* were also prevalent at all sites.

Group E2.

E2 sites were found on gentle hill slopes where drainage was moderate, uppermost substrates were > 90% silt, shallow surficial deposits overlie bedrock or till sheets, and acidic tundra was underlain by cryofacies assemblages of primarily syngenetic, segregated-ice cryostructures (Table 4 and Figure 9). Contemporary soils averaged 99% silt layers with minimal microtopography on slopes averaging 5° (sd = 2.5°). At least two landscape settings were associated with class E2: 1) mid and lower hill slope settings in broad valleys on glacial till sheets with a loess cap, and 2) on upper hill slope settings where a loess cap sits atop highly fractured, noncarbonate, near-surface bedrock. Primarily syngenetic cryofacies within the parent material occasionally included isolated lenses of intrusive, massive, or epigenetic cryostructures, or were (rarely) ice-poor. Upper substrates were greater than 90% silt (by particle size distribution) regardless of setting or evidence of colluvial processes. Upper permafrost within loess contained 25 to 70% segregated ice by volume, primarily including reticulate, ataxitic, and bedded cryostructures, with occasional lenticular structures or veins.

Vegetation was dominated by moist acidic tundra (Walker and Maier 2008), almost exclusively of the Upland Dwarf Birch-Tussock Shrub ecotype, which has an average soil pH of 4.7 (0.7 standard deviation reported for sites in northern foothills of the Brooks Range in Alaska (Jorgenson et al. 2010b). Organic layer depth averaged 21 cm (min 15 cm, max 23 cm), with moss-dominated peat. Dominant vegetation included *Eriophorum vaginatum, Betula nana* and dwarf and low willow and ericaceous species with a *Sphagnum* and feathermoss understory.

Subgroups ‘a’ and ‘b’ were distinguished by total organic layer depth (O_a). Subgroup 'a' had an average total organic-layer depth of 15 cm (sd = 4.5 cm) whereas subgroup 'b' averaged 22 cm (sd = 7.7 cm). The two subgroups partially coincide with regional geography (Figure 8) and strongly correlate with estimated time since last deglaciation. More than 85% of landscapes containing sites in subgroup ‘a’ occurred on late-Pleistocene/Holocene surfaces. Those of subgroup ‘b’ occurred on mid to late-Pleistocene surfaces, with more than 40% estimated as mid-Pleistocene (Hamilton 2003, Hamilton 2010).

Group E3.

E3 occurred on thin deposits of silty colluvium over near-surface bedrock, typically on upper hill slopes near exposed-bedrock hilltops, where ambient slope averaged 5.4° (sd = 1.3°; Table 4 and Figure 9). Nonacidic, primarily herbaceous vegetation occurred atop one to many deposits of colluvial material and syngenetic cryostructures, with interleaved layers or turbated fragments of relict vegetation. In contrast with other groups, substrate composition was relatively similar and consistent among sites. Colluvial surficial deposits were an admixture of silt and angular rubble, with silt generally comprising most of the material in the contemporary soil (mean = 90%; sd = 9%) versus a more even proportion in the parent material (mean = 68%; sd = 19%). Most sites occurred on hill slopes below exposed outcrops of micaceous shales containing < 1% quartzite in thin veins. The silt component frequently derived from some proportion of Pleistocene and Holocene loess (Hamilton 2010) mixed with silts from weathered shale, though the proportion is unknown either for any specific site or for these sites as a whole. Clast lithology was a mixture of shale and quartzite. Generally, increased distance from exposed bedrock correlated with increased proportion of weathering-resistent fragments of quartzite. Permafrost profiles were almost exclusively composed of syngenetic cryostructures, with an average 29 % (sd = 16 %) segregated ice by volume (visible ice). Ataxitic and reticulate cryostructures were typically co-dominant, with ice-rich transition zones at both current and relict permafrost tables. Vegetation was nonacidic, with a community gradient appearing to correlate with surface hydrology. Communities situated near or within preferential surface flowpaths contained higher proportions of non-tussock forming sedges (*Eriophorum angustifolium, Carex spp.*) with sparse cover of dwarf shrub (e.g., *Cassiope tetragona, Dryas* spp. *Salix* spp.) and low shrub (*Salix* spp.), and an understory of feathermosses. The wettest sites supported relatively deep surface organic layers of up to 33 cm of feathermoss-dominated material, with up to 20 cm of diffusely-flowing water on the ground surface. Dwarf shrub, forb and low shrub cover increases moving away from the hydric end of the gradient, with rapidly decreasing *E. angustifolium* cover. This group was distributed primarily in the Noatak Basin (Figure 8), with only one site found in the North Slope foothills.

Group E4.

Sites in group E4 were distributed across a highly variable suite of lowland sites where deep, ice-rich, non-carbonate glacial deposits underlie acidic or nonacidic low shrub communities. The most prominent common characteristic of this group was a deep deposit of ice-rich, diamictous, glacial till of primarily or exclusively noncarbonate lithology. At more than half of these sites, glacial till was overlain by, or interspersed with, glaciolacustrine, glaciofluvial, fluvial, or aeolian deposits, and typically appeared within kettle topography, on lower hill slopes, or along contemporary or relict river bluffs. The coarse fraction varied from 1 % to 75 % of the parent material by volume, including clast sizes from gravel to 2 m wide boulders (Table 4 and Figure 9). Massive ice was typically present in at least one form, including relict glacial ice, injection ice, and ice wedges. Ice wedges ranged from absent to

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dominant (> 90 % by volume) within the permafrost profile. Contemporary soils frequently included a loess cap, or less frequently appeared to develop directly from glacial deposits. Ataxitic and reticulate cryostructures were common, indicative of syngenetic permafrost development in the upper horizons. Vegetation was typically dominated by low shrubs, with both acidic and nonacidic vegetation observed. While low shrubs tended to dominate across sites, community composition and organic-layer depth varied markedly among these sites. Tussock cover ranged from absent to > 50 % cover.

Subgroupings were driven by outlier values for specific site properties. Subgroup 'a' represents the general characteristics of sites in this group. Subgroup 'b' included sites where ice wedges comprise > 40 % of the permafrost by volume. Subgroup 'c' was restricted to two sites within the same glacial deposit in the North Slope foothills containing > 75 % coarse fraction in the permafrost, with multiple boulder size clasts up to 1.9 m.

3.2 Relationships among sites and groups

Spatial distribution of groups of sites partially corresponded with regional geography (Figure 8). While sites from all four groups occurred both on the North Slope and within the Noatak Basin, all groupings exhibited regional tendencies. E1 sites had the strongest geographic affiliation, with five out of six sites concentrated within a 25-km radius in the upper Noatak Basin. Sites grouped E2 were more common on the North Slope, with only two examples in the Noatak Basin, while E3 was distributed throughout the Noatak Basin, but occurred only once on the North Slope. E4 sites occurred across the study region, however, only one of its three subgroups (E4a) was evenly distributed, with E4b primarily located in the Noatak Valley bottom, and E4c comprised of only two sites, both located within the same surficial geologic deposit on the North Slope.

The two sites grouped E4c behaved as outliers within the initial run of the MFA ordination, and were removed in the final ordination. These two sites were distinct in the sample, containing > 75% boulder-sized (600–1900mm) clasts by volume in the near-surface parent material, which was characteristic of that local moraine deposit. Removal of these two sites produced a more even spread of the remaining sites along graphed ordination axes, indicating a better representation of total variability among all sites. These two sites (36 and 38) were added back into the final grouping hierarchy as a subgroup, because all other site properties were comparable to those of the primary group with which they were associated in the pilot ordination.

4. Discussion

Broad-scale modelling of permafrost and terrain properties is frequently limited by the variability of relationships among regions, which is difficult to quantify and describe due to the cost of field sampling to characterize conditions and relationships within regions (Riseborough et al. 2008). As a result, maps of permafrost distribution and properties are either broad in scale but very general in content, or more specific in content but limited in spatial scale (Jorgenson et al. 2008b, Gruber 2012, Jorgenson et al. 2014, Pastick et al. 2014). Results from this study should support and inform future modelling of permafrost conditions in the central and western Brooks Range by providing further evidence of the relationship between permafrost conditions and landscape characteristics, and by illustrating the nature of these relationships for this region.

No single terrain factor emerged as the dominant driver of permafrost conditions in our study region. For example, while soil coarse fraction was a strongly influential factor driving the ordination, considered alone it failed to explain key differences among sites and groupings. Groups E1 and E3 (Figure 5) both comprised sites with gravelly surficial substrates, but sites grouped E1 occurred in xeric to mesic conditions with *Dryas*-dominated vegetation and ice-poor permafrost, while E3 sites were located in more hydric settings with wet sedge meadow vegetation and primarily reticulate and syngenetic cryostructures, frequently including an ice-rich transition zone. As no single factor was identified as a dominant driver of the ordination, estimation of upper permafrost conditions by proxy should incorporate multiple terrain factors.

Gradients and divisions among sites and site groupings were driven by terrain properties that generally correspond with state factors, suggesting that examination of properties organized by state factor may provide better insight and more complete, parsimonious information for estimating landscape permafrost conditions. MFA blocks representing vegetative and substrate factors were important, complementary drivers in the ordination, and correspond with two of the five state factors (biota and parent material). The data reduction step in our analyses revealed key index variables in the data, which were correlated with multiple variables organized within logical data blocks. At landscape to regional scales, selection of the most statistically relevant and representative index variables from groups of variables defined by state factors may offer the most parsimonious method for analyzing terrain properties driving upper-permafrost characteristics. The complexity, broad diversity, and remote nature of landscapes throughout the Low Arctic present difficult challenges for estimating subsurface conditions, such as permafrost, which are fundamental to landscape processes and critical to understanding climate change impacts and feedbacks at regional scales. Exploiting relationships among terrain and permafrost properties within a state factor framework may offer the most effective and efficient approach for estimation of permafrost-related properties and processes in remote, arctic regions.

Results of this analysis are also suggestive of the spatial distribution of prevalent ecological processes including paludification and development of the permafrost intermediate layer through

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quasi-syngenetic permafrost aggradation (Shur 1988), and support the idea that these relationships may be modelled to better understand landscape distributions of cryofacies (French 1998, Shur and Jorgenson 2007, Jorgenson et al. 2014). Together, these provide insights for conceptual models of landscape development and response (Jorgenson et al. 2010a), which in turn can be empirically tested at landscape to regional scales using structural equation modeling, integrated terrain unit analysis, and other approaches which rely upon a-priori knowledge from which to construct initial models. Also, the results help identify which permafrost, vegetation and terrain properties may be most germane for modelling within this region, enabling more efficient and targeted field data collection.

Results of this study further support prior findings correlating permafrost properties and vegetation with terrain conditions (Kreig and Reger 1982, Pullman et al. 2007, Kanevskiy et al. 2011), identifying which permafrost, vegetation and terrain factors are most closely correlated, and illustrating specific examples of these relationships from landscapes within our study region. The correlations of terrain conditions across a diversity of sites may provide for proxy estimation of certain permafrost properties within this region (Figures 5 - 7). Whereas our groupings of sites were at least partially a product of biased sampling, the groupings demonstrate that specific terrain properties are correlated with surficial conditions across a diversity of landscapes in the region, and that they likely influence surficial conditions in a generally consistent manner along landscape gradients. Relative estimates of some subsurface properties should therefore be possible across landscapes in the study region.

These results are generally consistent with those obtained from studies of other, differing permafrost regions and studies conducted at different scales, and offer detail for this region to support modelled estimates of permafrost properties. General relationships among terrain, vegetation, active layer and upper permafrost horizon properties and cryostructures have been described for regions throughout the Arctic (Wolfe et al. 2001, Shur and Jorgenson 2007, Raynolds and Walker 2008, French and Shur 2010, Daanen et al. 2011, Jorgenson et al. 2013, Mishra and Riley 2014, Pastick et al. 2014) and for specific localities (Viereck 1973, Murton and French 1994, French 1998, Walker et al. 2008), and support early assertions of a general correlation between upper permafrost conditions and landscape characteristics throughout the Arctic (Washburn 1980, Shur 1988). While inter-related correlations among terrain, vegetation, and permafrost have been found at broad scales throughout the Arctic (Shur and Jorgenson 2007, Raynolds and Walker 2008, Kokelj and Jorgenson 2013), the nature and strength of relationships among terrain, vegetation and permafrost vary significantly by region (Shur and Jorgenson 2007, Jorgenson et al. 2010a, Pastick et al. 2014).

5. Conclusions

Correlations among terrain and permafrost properties offer opportunities to better understand distributions of ground ice and cryostructures, and provide evidence of cryogenic processes across landscape gradients. Statistically-supported groupings of sites across a broad diversity of landscapes suggest consistent, though complex, inter-relationships among terrain and permafrost properties in the study region. These are a potential basis for improved spatially-explicit, proxy estimations of conditions in upper permafrost horizons, and for identifying areas prone to particular modes of permafrost degradation in response to climate warming and disturbance across the study region. In the Brooks Range and foothills of northern Alaska, where diverse landscapes abutting the arctic-boreal ecotone may be especially prone to multiple modes of permafrost degradation with climate change, and where remote settings severely limit direct observation of permafrost properties, this multi-factor approach facilitates better estimation of extents, trajectories and magnitudes of different permafrost degradation modes and their future impacts.

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Table 1. Variables characterizing conditions in the vicinity of each permafrost profile exposure.

Segment	Name	Type		Source
Landscape	Physiographic position	Categorical	*	Jorgenson et al., (2010b)
Landscape	Surficial Geology	Categorical	*	Hamilton, (2003 & 2010)
Landscape	Lithology	Categorical	*	Jorgenson et al., (2010b)
Landscape	Bedrock Geology	Categorical	§	Beikman (1982)
Landscape	Glacial Geology	Categorical	§	Hamilton, (2003 & 2010)
Site Surface	Elevation	Quantitative	*	Garmin eTrex GPS
Landscape	Elevation	Quantitative	§	ASTER DEM
Site Surface	Slope	Quantitative	*	Brunton inclinometer
Landscape	Slope	Quantitative	§	ASTER DEM
Site Surface	Aspect	Quantitative	*	Brunton compass (declination adjusted)
Landscape	Aspect	Quantitative	§	ASTER DEM
Landscape	Topographic Position Index	Quantitative	§	ASTER DEM, Jenness (2006)
Landscape	Macrotopography	Categorical	*	Jorgenson et al., (2010b)
Site Surface	Microtopography	Categorical	*	Jorgenson et al., (2010b)
Landscape	Geomorphic unit	Categorical	*	Jorgenson et al., (2010b)
Site Surface	Permafrost degradation mode	Categorical	*	Jorgenson et al., (2008a)
Site Surface	Vegetation	Categorical	*	Viereck et al., (1992); Jorgenson et al., (2010b)
Landscape	Vegetation complex	Categorical	§	Walker et al., (2005); Jorgenson et al., (2010b)
Site Surface	Dominant flora [over & understory]	Species	*	Hulten (1968) & Parker (2006)
Landscape	Summer Warmth Index	Quantitative	§	Raynolds et al., (2008b)
Site Surface	Ecotype	Categorical	*	Jorgenson et al., (2010b)
Site Surface	Acidic (from mean pH per Ecotype)	Categorical	*	Jorgenson et al., (2010b)

* assessed and recorded in the field
§ derived from spatial (GIS & remote sensing) analyses

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Table 2. Variables characterizing soil and permafrost properties in the vicinity of each permafrost profile exposure.

Name	Segment	Type		Integrator Variable	Units / Source
Depth of Active Layer	Profile	Quantitative			cm
Total Depth of Profile	Profile	Quantitative			cm
Wedge/Intrusive Ice Percentage	Profile	Quantitative			% of profile exposure
Fibric/Hemic Thickness (O_i / O_e)	Soil	Quantitative			cm
Sapric Thickness (O_a)	Soil	Quantitative			cm
Depth of Contemporary Soil	Soil	Quantitative			cm
Coarse Fraction Percentage	Soil	Quantitative	§	Coarse & Fine Fraction	% of profile exposure
Maximum Clast Size	Soil	Quantitative	*		cm
Segregated Ice Percentage	Soil	Quantitative	*		% of profile exposure
Segregated Ice Max. Width	Soil	Quantitative	*		cm
Lithofacies	Soil	Categorical	§	Coarse & Fine Fraction	Jorgenson et al., (2010b)
Coarse & Fine Fraction	Soil	Categorical			Jorgenson et al., (2010b)
Coarse Fraction Shape	Soil	Ordinal	*		Jorgenson et al., (2010b)
Peat Type	Soil	Categorical	*		Jorgenson et al., (2010b)
Primary Cryostructures	Parent	Categorical			Jorgenson et al., (2010b)
Secondary Cryostructures	Parent	Categorical	*		Jorgenson et al., (2010b)
Lithofacies	Parent	Categorical	§	Coarse & Fine Fraction	Jorgenson et al., (2010b)
Coarse & Fine Fraction	Parent	Categorical			Jorgenson et al., (2010b)
Coarse Fraction Shape	Parent	Ordinal			Jorgenson et al., (2010b)
Buried Organics Percentage	Parent	Quantitative			% of profile exposure
Primary Cryostructures	Parent	Categorical			Jorgenson et al., (2010b)
Secondary Cryostructures	Parent	Categorical			Jorgenson et al., (2010b)
Coarse Fraction Percentage	Parent	Quantitative	§	Coarse & Fine Fraction	% of profile exposure
Maximum Clast Size	Parent	Quantitative	§	Coarse & Fine Fraction	cm
Segregation Ice Percentage	Parent	Quantitative			% of profile exposure
Segregation Ice Max. Width	Parent	Quantitative			cm

* excluded from MFA analysis; Pearson's r < .300 in pilot ordination
§ excluded from MFA analysis; information captured within a separate integrator variable (Pearson Correlation)

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Table 3. Active (response) and supplemental (explanatory) variables used for statistical analysis, and subsequent grouping by hierarchical clustering. Active variables drive ordination results, while supplemental variables are used as overlays on ordination graphs to examine correspondence of that variable with ordination results.

Name	Block	Type	Class
Vegetation class	Vegetative	Categorical	Active
Acidic	Vegetative	Categorical	Active
Litter Layer Thickness (O_i)	Vegetative	Quantitative	Active
Organic Layer Thickness (O_a)	Vegetative	Quantitative	Active
Buried Organics Percentage	Vegetative	Quantitative	Active
Depth of Contemporary Soil	Substrate	Quantitative	Active
Depth of Active Layer	Substrate	Quantitative	Active
Coarse Fraction Percentage (contemporary soil)	Substrate	Quantitative	Active
Microtopography	Substrate	Categorical	Active
Coarse & Fine Fraction (contemporary soil)	Substrate	Categorical	Active
Coarse & Fine Fraction (archaic soil/parent material)	Substrate	Categorical	Active
Ice percentage	Ice	Quantitative	Active
Segregated Ice Maximum Lens Width	Ice	Quantitative	Active
Wedge/Intrusive Ice Percentage	Ice	Quantitative	Active
Total Depth of Profile	Ice	Quantitative	Active
Primary Cryostructures	Ice	Categorical	Active
Secondary Cryostructures	Ice	Categorical	Active
Acidity (mean Ecotype pH)	n/a	Quantitative	Supplemental
Elevation	n/a	Quantitative	Supplemental
Aspect	n/a	Quantitative	Supplemental
Topographic Position Index	n/a	Quantitative	Supplemental
Summer Warmth Index	n/a	Quantitative	Supplemental
Slope	n/a	Quantitative	Supplemental
Surficial Geology	n/a	Categorical	Supplemental
Bedrock Geology	n/a	Categorical	Supplemental
Glacial Geology	n/a	Categorical	Supplemental
Vegetation Complex	n/a	Categorical	Supplemental
Ecotype	n/a	Categorical	Supplemental
Lithology	n/a	Categorical	Supplemental
Macrotopography	n/a	Categorical	Supplemental
Permafrost Degradation Mode	n/a	Categorical	Supplemental
Lithofacies	n/a	Categorical	Supplemental

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Table 4. Summary values for field-estimates characterizing soil and permafrost properties in the vicinity of each permafrost profile exposure, presented by grouping from hierarchical clustering of MFA ordination results.

	Units	Segment	E1		E2		E3		E4	
			mean	std	mean	std	mean	std	mean	std
Elevation	m	Site	576	70	633	240	657	167	469	314
Slope	°	Site	5.7	0.8	5.0	2.5	5.4	1.3	9.4	4.0
Aspect	°	Site	251	102	216	110	128	109	165	119
Depth of Active Layer	cm	Profile	156	55	58	16	82	21	64	23
Total Depth of Profile	cm	Profile	432	230	133	45	175	66	382	272
Wedge/Intrusive Ice	%	Profile	16	16	3	7	0	0	23	25
Litter Layer Thickness (O_i)	cm	Soil	1.5	0.5	9.3	5.6	6.1	4.6	3.9	2.1
Organic Layer Thickness (O_a)	cm	Soil	7.3	6.6	20.6	7.8	21.2	8.6	10.9	7.3
Depth of Contemporary Soil	cm	Soil	63	31	42	13	57	9	52	33
Coarse Fraction	%	Soil	15	9	1	3	10	9	9	20
Maximum Clast Size	cm	Soil	50	18	8	17	42	44	63	118
Segregated Ice	%	Soil	0	0	3	8	0	0	1	4
Segregated Ice Max.Width	mm	Soil	0	0	3	7	0	0	7	28
Buried Organics	%	Parent	3.5	6.2	8.8	6.9	7.0	8.7	6.3	7.3
Coarse Fraction	%	Parent	32	4	12	16	32	19	32	22
Maximum Clast Size	cm	Parent	501	332	41	41	88	46	559	483
Segregated Ice	%	Parent	9	15	29	19	29	16	56	24
Segregated Ice Max.Width	mm	Parent	75	86	65	107	52	55	947	1017

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Table 5. Site groupings compared by permafrost degradation mode.

Site Grouping	Permafrost Degradation Mode				
	ALDS	Soil Pit	RTS	TEG	Total
E1	0	0	6	0	6
E2a	4	0	1	2	7
E2b	2	1	6	8	17
E3	7	0	2	0	9
E4a	0	0	3	0	3
E4b	0	0	9	1	10
E4c	0	0	2	0	2
Total	13	1	29	11	

ALDS = Active Layer Detachment Slide
RTS = Retrogressive Thaw Slump
TEG = Thermo-Erosional Gulley

Table 6. Field sites by group with ground coordinates (Geographic decimal degrees, NAD83).

Site	Name	Group	Subgroup	Latitude	Longitude
19	Third Twin A	E1		67.95835	-156.81985
20	Third Twin B	E1		67.95835	-156.81985
21	Third Twin C	E1		67.95835	-156.81985
22	Good Twin	E1		67.95929	-156.78624
23	Woodpile	E1		67.89927	-156.48472
34	Itkillik-2	E1		68.66615	-149.81720
6	Sushi	E2	a	67.86342	-161.48044
9	Bear Patch	E2	a	67.73697	-161.42747
25	Cotton Hollow	E2	a	68.98551	-150.71714
26	VoTK	E2	a	68.96278	-150.67086
47	GTH89	E2	a	68.52534	-149.54644
50	I-Minus-2 A	E2	a	68.54345	-149.52273
53	TRTK A	E2	a	68.69177	-149.20751
24	Helios	E2	b	68.91054	-150.74004
27	VoTK	E2	b	68.96067	-150.66970
28	VoTK Control	E2	b	68.96210	-150.66755
31	Ptarmigan Bluff	E2	b	68.87620	-150.54552
32	Horn Lake A	E2	b	68.96068	-150.31443
33	Horn Lake B	E2	b	68.96068	-150.31443
39	Nstk-3u A	E2	b	68.87147	-149.57768
40	Nstk-3u B	E2	b	68.87148	-149.57768
41	GTH88 A	E2	b	68.50785	-149.57474
42	GTH88 B	E2	b	68.50806	-149.57433
43	I-Minus-1 A	E2	b	68.55244	-149.57229
44	I-Minus-1 B	E2	b	68.55253	-149.57169
45	I-Minus-1 C	E2	b	68.55231	-149.57081
49	GTH89 A	E2	b	68.52510	-149.53815
51	I-Minus-2 B	E2	b	68.54337	-149.52260
52	GTH86	E2	b	68.61919	-149.42786
54	TRTK H	E2	b	68.69360	-149.20430
5	Remora	E3		67.64853	-161.60562
7	Saddle	E3		67.81790	-161.44655
8	Eli	E3		67.71618	-161.43026
10	Slopbucket	E3		67.92515	-161.41811
14	Old Ironslides	E3		68.27005	-157.68447
16	Mafic Monks	E3		68.26651	-157.47338
17	Jaded Plover	E3		67.98045	-157.07511
18	Bloodslide	E3		68.28070	-157.05966
37	GTH88 C	E3		68.50267	-149.58873
2	Rainbucket	E4	a	67.94305	-162.35649
4	Loon Lake A	E4	a	67.92730	-161.96506
12	Quebec	E4	a	68.08735	-158.04102
13	Gavia Familia	E4	a	68.08324	-158.02727
15	Cutler Ice	E4	a	67.87649	-157.53053
29	Lobelia A	E4	a	68.87938	-150.55647
30	Lobelia B	E4	a	68.87938	-150.55647
35	NE-14	E4	a	68.67904	-149.62320
46	I-Minus-1 D	E4	a	68.55272	-149.56517
48	GTH89 B	E4	a	68.52585	-149.54500
1	Wulik	E4	b	67.84770	-163.88159
3	Loon Lake B	E4	b	67.92794	-161.97230
11	Grandaddy	E4	b	68.03481	-159.29156
36	GTH88 D	E4	c	68.50268	-149.58901
38	GTH88 E	E4	c	68.51121	-149.58395

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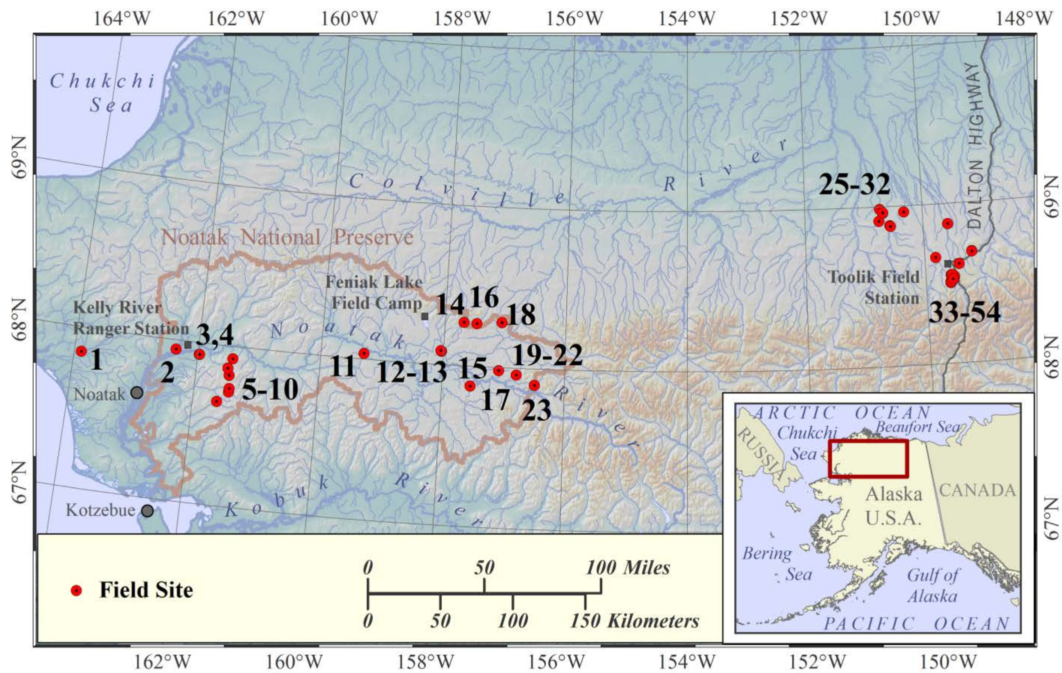

Figure 1. Study region in northern Alaska. Field sites were identified and selected through aerial survey, with ground visits by helicopter from Feniak Lake Camp and Kelly River Ranger Station in the Noatak National Preserve, and by helicopter and on foot from Toolik Field Station on Alaska's North Slope.

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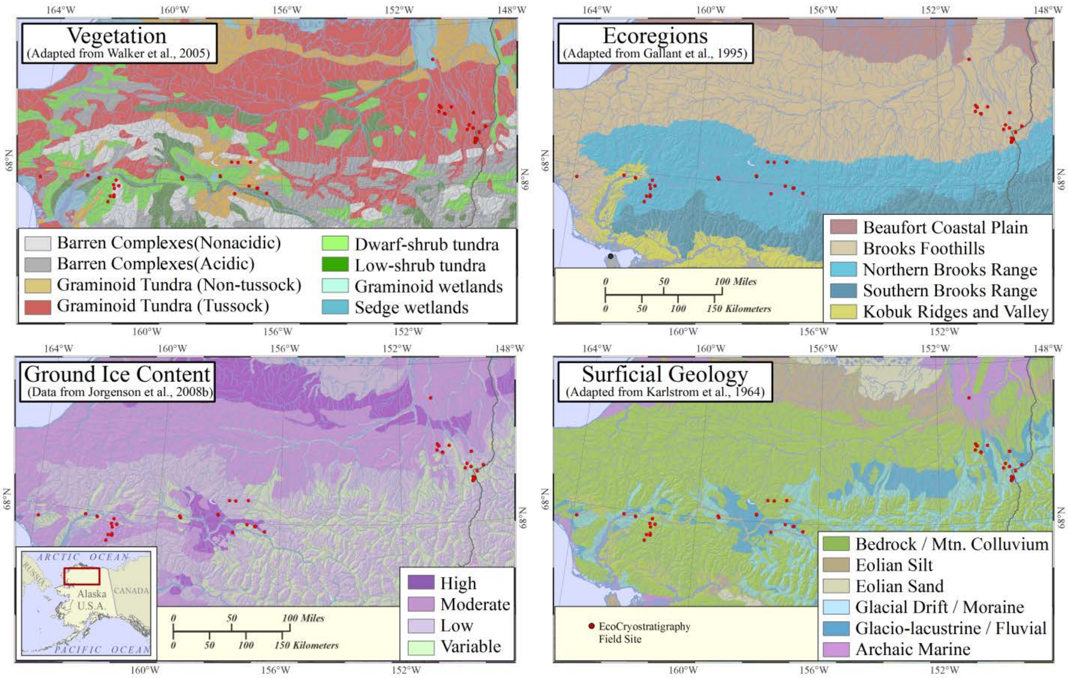

Figure 2. Generalized landscape characteristics of the study region. All field sites (red dots) are within the continuous permafrost zone (Jorgenson et al. 2008b), within Arctic Bioclimate Subzone E (CAVM-Team 2003), and are generally Climate-driven Ecosystem-modified permafrost landscapes (Shur and Jorgenson 2007). While these ancillary data sets provide valuable insight into regional landscape composition, this study is focused on terrain and upper permafrost horizon properties at finer scales.

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Figure 3. Permafrost degradation features providing access to permafrost profile exposures. Photos show (upper, a) general morphology from oblique airphotos and (lower, b) unprepared permafrost exposures from ground photos. Retrogressive thaw slumps (1), thermo-erosional gullies (2) and active layer detachment slides (3) were the predominant permafrost degradation features in the study area and comprised all feature types examined in this study. Photos 2a and 2b courtesy W. B. Bowden.

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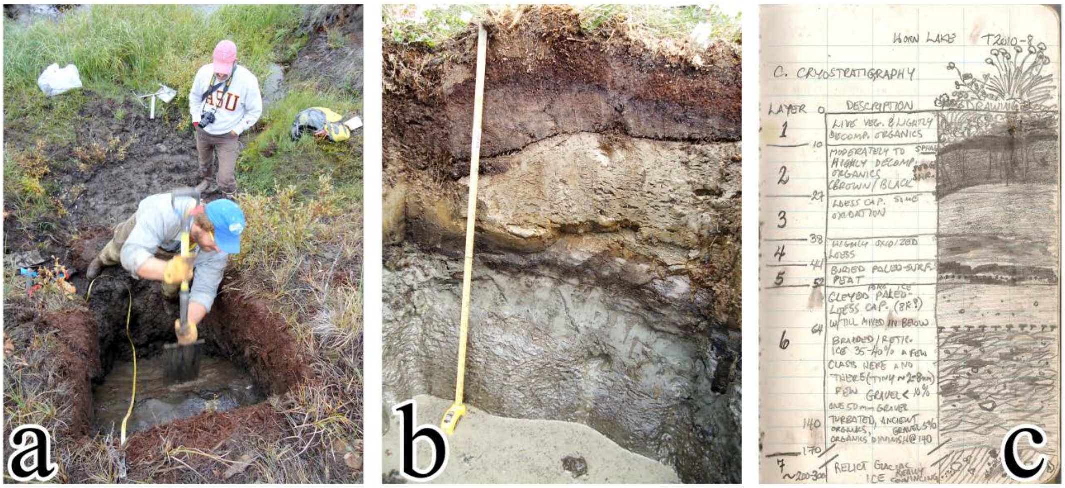

Figure 4. Upper permafrost profile exposure. Photos show (a) profile preparation, (b) a profile prepared for examination, and (c) schematic cryostratigraphic map of the permafrost profile, substrate and vegetation, which complements tabular data for each profile layer.

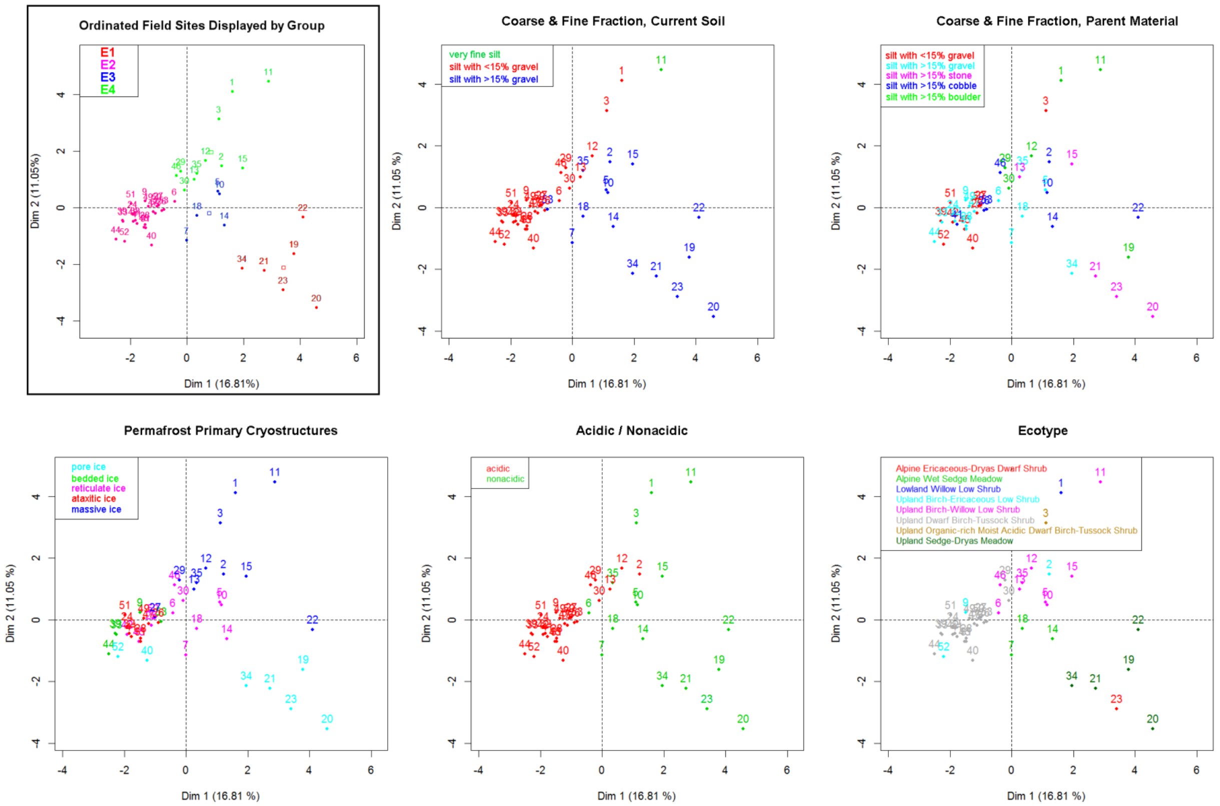

Figure 5. Field sites displayed by grouping (box, upper left), and with active categorical variables overlain on graphed MFA results. Colors of groupings correspond with the dendrogram and map (Figures 7 &8).

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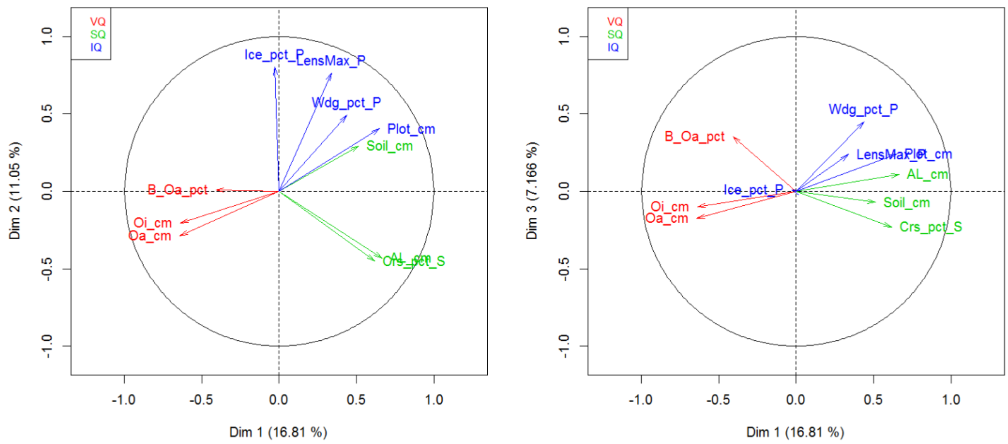

Figure 6. Influence of quantitative variables, shown by block, on the 3-dimensional MFA ordination driving clustered site groupings. Variables are shown by MFA block: VQ (red) = Vegetative, SQ (green) = substrate, IQ (blue) = Ice/Permafrost. MFA dimensions 1 and 2 are shown on left; MFA dimensions 1 and 3 are on the right.

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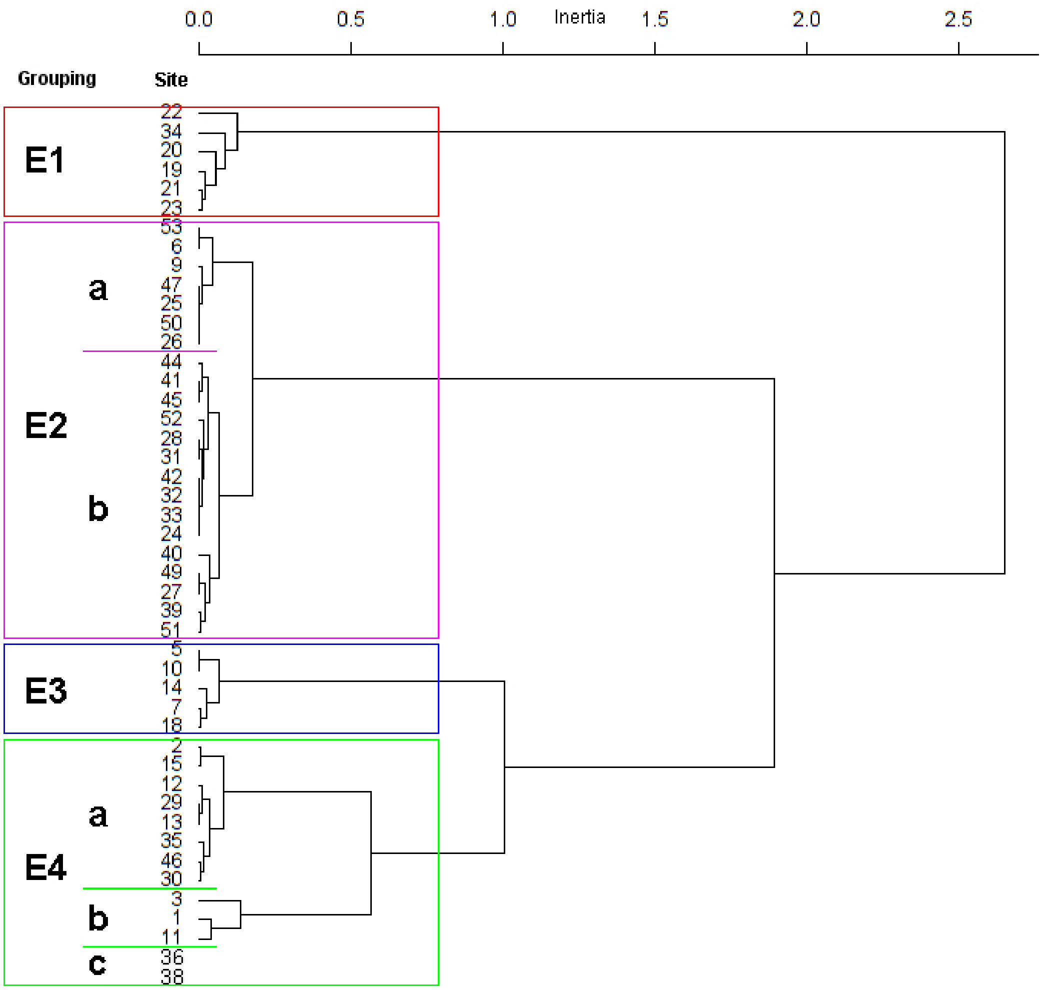

Figure 7. Dendrogram from hierarchic clustering of MFA results, showing groupings E1-E4. Colors correspond with ordination group overlay graph (Figure 5), and with map of sites by grouping (Figure 8).

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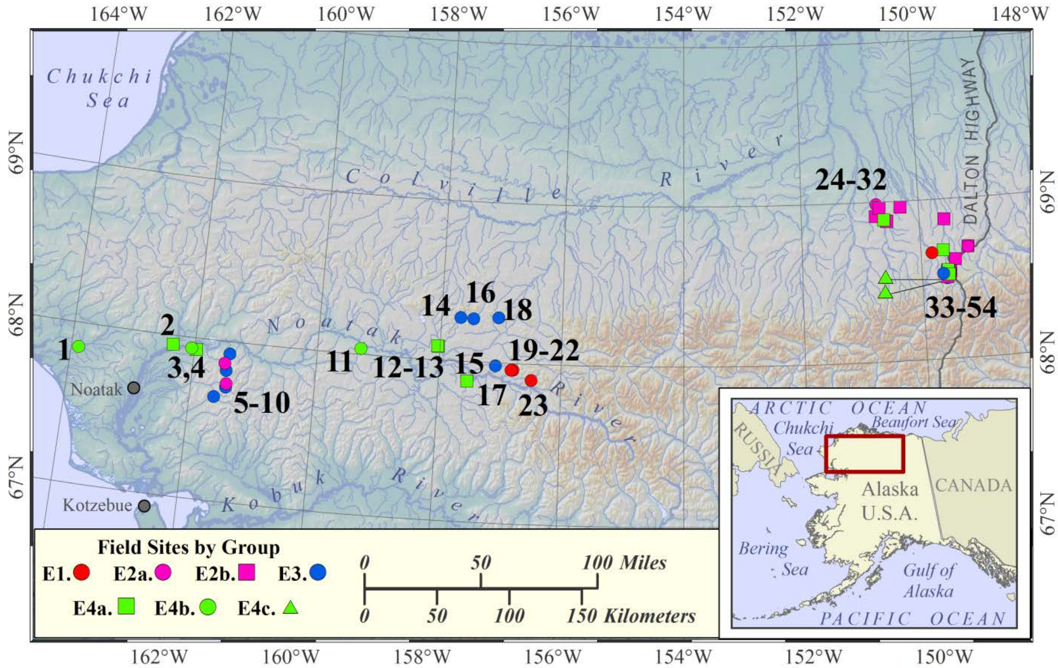

Figure 8. Distribution of field sites by grouping. E2a and E2b are similar sub-groups, differentiated mainly by the effects of a deeper organic horizon for E2a. E2 is found predominantly on the North Slope, with the two occurrences in the Noatak Basin of subtype ‘a’, possibly associated with warmer, drier conditions compared with a stronger maritime influence promoting cooler and damper summertime conditions on the north slope. E3 is found only once on the north slope, but is more common in the Noatak Basin associated with noncarbonate colluvial deposits prevalent on upper hill slopes there. We consider all of these sites to occur within Climate-Driven Ecosystem-Modified permafrost landscapes proposed by Shur and Jorgenson (2007), and all occur within Arctic Bioclimate Subzone E (CAVM-Team 2003).

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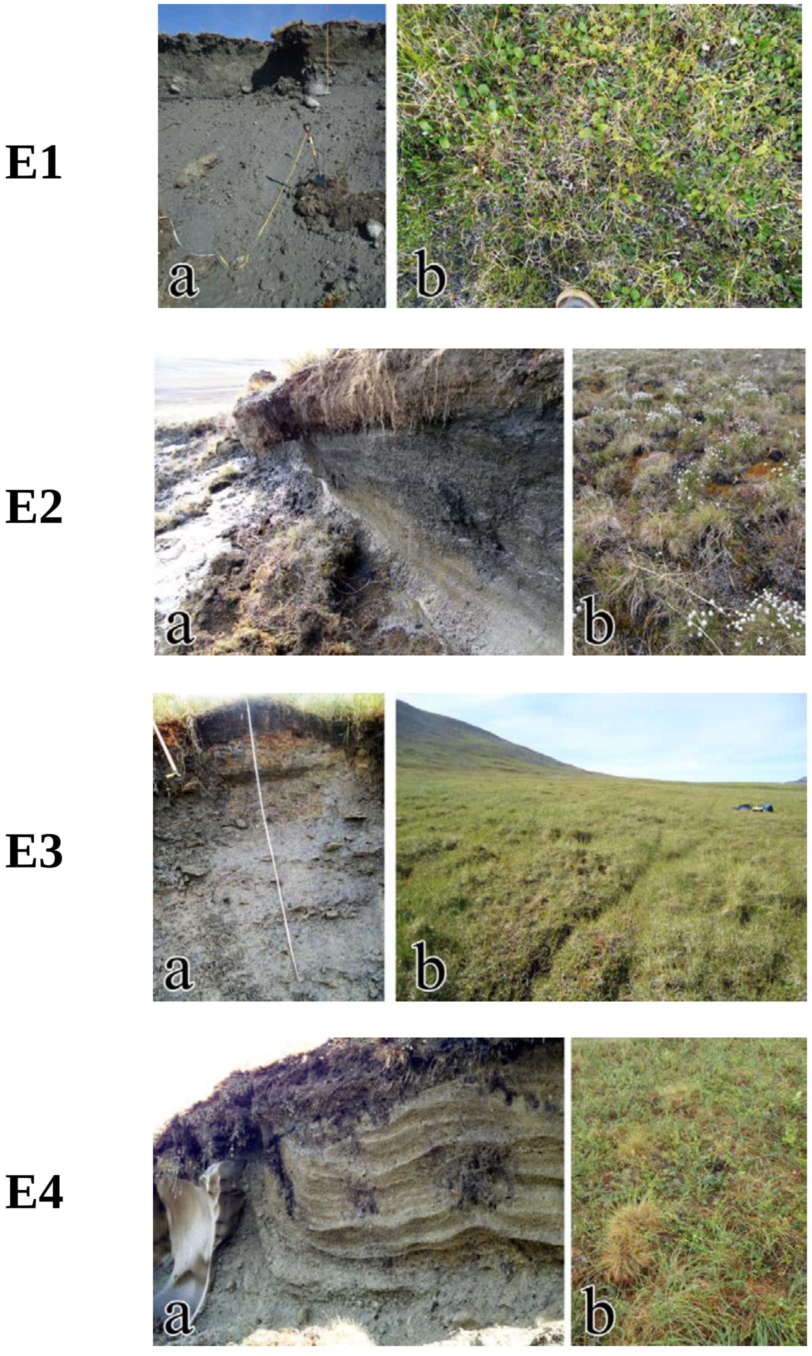

Figure 9. Photos of sites from groups E1, E2, E3 and E4. 'a' = substrate and upper permafrost profile, 'b' = vegetation. E1. is Site 19; E2. is Site 25; E3. is Site 18; E4. is Site 15.