Soils Associated with Biotic Activity on Frost Boils in Arctic Alaska

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Frost boils occur extensively across arctic tundra ecosystems, and biotic crusts form on the mineral soils exposed in centers of boils. These center areas of the frost boils eventually become completely covered by tundra vegetation. We studied the biogeochemistry of the surface soils (0- to 10-cm depth) on frost boils at nine sites across a soil pH gradient in arctic Alaska. Soils under biotic crusts were compared with adjacent bare and fully vegetated areas within the centers of the same boil. Near the sea coast we found segregation of Na salts to the bare surface areas of boils and concentration of Ca under adjacent crusted areas within the boils. In contrast, inland coastal plain soils with nonacidic tundra showed Ca accumulation under both crusted and vegetated areas within the boils. Nonacidic soils rich in inorganic C were effective at buffering pH changes with organic carbon (OC) accumulations of up to 200 g kg^{-1}. Soil water-soluble OC (OCws) stocks of nonacidic boil sites correlated well with soil total OC (R^2 = 0.62, p < 0.01), while OCws for boils formed in acidic soils was correlated to total soil N stocks (R^2 = 0.69, p < 0.01), consistent with there being different limitations to soil biological activity for soils across the soil pH gradient. Although there were differences in quantity of accumulated organic matter across the soil pH gradient, soil nutrient pools increased as OC accumulated under crusted and then vegetated soils across all sites.

Abbreviations: BD, bulk density; BS, base saturation; CEC, cation exchange capacity; IC, inorganic carbon; ICP, inductively coupled plasma; MAT, moist acidic tundra; MNT, moist nonacidic tundra; OC, organic carbon; OCws, water-soluble OC; OM, organic matter; TN, total nitrogen

Nonsorted circles or frost boils (Washburn, 1956; Walker et al., 2008) are common features throughout permafrost regions and are a significant component of circumpolar arctic tundra ecosystems (Chernov and Matveyeva, 1997). They are recognizable as <1- to 2-m diam. circular shapes of mineral or sparsely vegetated soil that have more vegetation cover along the outer circle and between circles than within the circle. These circles can occur in net-like patterns over the landscape or as patterns within ice-wedge polygons (Shilts, 1978; Walker et al., 2008). In arctic Alaska the exposure of bare or crusted mineral soil within frost boil patterns covers 1 to 10% of the ground surface for moist acidic tundra (MAT) and moist nonacidic tundra (MNT) areas (Walker et al., 1998; Bockheim et al., 1998). However, frost boils have much more of an impact on soil properties than might be indicated by the extent of bare surface soil that is readily observed. Investigations of soil profiles to 1 m by Ping et al. (1998) revealed that it is common for soils of both MAT and MNT landscapes to contain evidence of extensive frost boil activity to depth. In many areas frost boils are completely vegetated or vegetated in patterns that mask the extent to which both current and past frost boil activity has affected soils. For example, on older landscapes in arc-

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tic Alaska, tussock tundra vegetation can easily mask the circular pattern of boils and the associated bare or crusted soil areas. Frost boil activity is recognized as having an important role in landscape–ecosystem evolution (Walker et al., 2008) and in maintaining plant diversity (Raynolds et al., 2008) in Alaska and across the Arctic (Chernov and Matveyeva, 1997). Frost boil activity plays a key role in such processes as cryoturbation, carbon sequestration, soil development, and active layer dynamics (Ping et al., 2008; Daanen et al., 2008; Walker et al., 2004).

As frost boils change and vegetation establishes on the bare soils of boil centers, the character of this vegetative cover and organic matter accumulation is very important in controlling the activity and evolution of the boils. Peterson and Krantz (2008) provided a mathematical model and Walker et al. (2008) provided a conceptual model for development and activity of frost boils. These features change form as they occur across the arctic north-south bioclimatic gradient. The role of vegetation community, plant cover on heat transfer, and soil water freezing dynamics control soil heave and thus frost boil expression (Kade and Walker, 2008). Daanen et al. (2008) modeled these insulating effects of various vegetation types, each having a different character in providing the insulating properties that control frost boil expression. Additionally, frost boil activity is a major factor in soil OC accumulation and sequestration through its contribution to cryoturbation and redistribution of surface-accumulated SOM into the soil profile (Ping et al., 2008; Michaelson et al., 2008).

The association of vegetation with soils, particularly with soil pH, has been studied along with vegetation effects on nutrient dynamics in arctic Alaska. For example, the character and diversity of tundra vegetation has been found to be dependent on the initial soil substrate chemistry. Soil reaction (pH) and nutrients present in arctic soils are known to influence which plant species will grow thus controlling the nutritional composition and value of plants present in the tundra (Bockheim et al., 1998; Walker et al., 1998; Hobbie and Gough, 2002). Landscape age and soil pH affects soil OC quality and dynamics (Whittinghill and Hobbie, 2011). However, there have been few studies that relate the effects of vegetation changes or development on soil biogeochemical properties of arctic soils. These effects could, however, be crucial as vegetation changes are some of the first noticeable effects of changing arctic climate (Sturm et al., 2005), and changes in soil nutrient status resulting from vegetation changes will be an important factor in determining any functional changes that happen in tundra systems, such as whether arctic soils will remain in the long-term a carbon sink or become sources for atmospheric greenhouse gasses (Mack et al., 2004).

Climate drives biomass production across the Arctic, and biomass is an integral part of frost boil dynamics that control carbon sequestration through cryoturbation of surface accumulated carbon into the lower soil horizons and the upper permafrost. Cryoturbated OC can account for 60% or more of soil stocks in the upper 1 m of soils (Michaelson et al., 1996, 2008; Ping et al., 2008). In all of the Arctic bioclimatic subzones, biotic crusts are commonly the first stage of soil vegetation cover that in the mid and lower subzones eventually leads to tundra establishment (Walker et al., 2011). Studies of biotic crust formations on soils of the polar desert (Bliss and Gold, 1999), the midlatitude Mojave Desert (Billings et al., 2003), and the Tengger Desert of northern China (Yang et al., 2010) all found that crusts are primarily important to ecosystem recovery, nitrogen fixation, and soil and microbial community development. But these and other studies focus on the biota and plants that make up crusts, not on the impacts of organic carbon accumulation and biotic activity on soil chemical and physical properties.

Biological activity in the exposed surface soil of the frost boil centers results in the formation of biotic crusts that are largely composed of nonvascular plants and other organisms (Walker et al., 2011). Crust activity causes biogeochemical changes in soils that contribute to the eventual establishment of full vegetative or tundra cover, and this cover serves to decrease or change the physically disruptive effects of frost heave and leads to a decrease in active layer depth. In the more active frost boils, soils exposed in center areas are usually contiguous with and have chemical and physical properties similar to subsurface soil B- or C-horizons. These surface-disrupted areas in boil centers often have minimal biochemical alteration or organic matter and nutrient additions (Ping et al., 1998; Michaelson et al., 2008). Therefore, the substantial changes that must occur for the development of these soils begins with crust establishment on the exposed mineral material, and changes intensify with vascular plant cover and soil organic matter accumulation on the surface. In frost boil systems cryoturbation then moves these now organic enriched surface materials into the active layer, and they become important stocks of biologically active carbon and nutrients affecting the properties of the entire soil profile (Michaelson and Ping, 2003, Ping et al., 2008). Thus in the arctic environment these surface soils in frost boil centers offer a unique opportunity for studying biotic effects on soil properties such as nutrients and OC accumulation.

Although arctic soils have been studied at the landscape and ecosystem scale and by whole pedon or by organic surface horizons, in this study we examine some of the influences of crust and tundra vegetation establishment on soils within the uppermost surface portion of the pedon. We compare the following: (i) barren surface soils to those with biotic crusts and with complete plant vegetative cover (developed organic horizons), (ii) the influences of these varying surface conditions on frost boils over the region's naturally occurring substrate pH gradient across arctic Alaska, and (iii) changes in characteristics of surface soils as crusts and vegetation mats are established. In making these comparisons we elucidate soil characteristics as they occur at the centimeter scale at the plant–soil interface. Our objectives are to examine how biological activity influences soil characteristics with the establishment of continuous tundra cover. By better understanding these biotic influences we gain insights into disturbance, function, and evolution of arctic ecosystems under changing conditions.

MATERIALS AND METHODS
Sampling

Frost boils were sampled at nine sites across arctic Alaska (Fig. 1). All sites (except No. 2 and No. 9) were adjacent to established National Science Foundation Biocomplexity of Patterned-Ground Study grids described by Walker et al. (2004, 2008). After examination of many frost boils at each sampling site, frost boils that had surface morphologies that were judged typical to the area were selected for sampling. Soil samples were collected in August and September of 2001 to 2002 and were from these characteristic individual frost boils at each study site. Frost boil centers that were sampled exhibited a full range of surface conditions within the same boil center. These surface conditions included three easily identifiable areas: exposed bare mineral soil, nonvascular biotic crusts, and full vegetation cover. Single frost boils were sampled at Sites 1, 2, and 9 with triplicate boils sampled at the other six sites. Depth increment samples were taken under a 15 cm by 15 cm square area and were collected by successive slicing and removal of soil under the 15 by 15 cm area with a knife starting from the surface. The surface 10 cm of soil was sampled at five depth increments. The uppermost depth increment collected varied in thickness from 0.5 to 4 cm depending on the nature of the surface and vegetation: thin cyanobacteria crust surfaces were sampled at 0.5 cm, other crusts or barren areas at 1- or 2-cm increments depending on apparent physical thickness of the crust, while organic layers under vascular plant vegetation were sampled using the thickness of the organic layer that varied from 1- to 4-cm thick for the first depth increment. After sampling the first increment representing the surface physical layer (for barren and crusted areas) or the organic horizon thickness (for vegetation mats), 2-cm thick increment samples were taken to a 10-cm depth for the underlying mineral soils. Dimensions for each of the incremental samples were recorded, and samples were sealed in plastic bags and weighed for determination of water content and bulk density after drying in the laboratory. A total of 112 samples were collected for this study. Soil surface-layer properties were compared for micro sites found within frost boil centers. Micro sites compared are barren, crusted, and fully vegetated areas from within the same frost boil.

Soil Analyses

Soils at each site were described according to the USDA-NRCS field guide (Schoeneberger et al., 2002). Surface area coverage by frost boils was estimated from aerial photos. Tundra classifications were taken from Walker et al. (2004). Laboratory analyses were performed at the University of Alaska Fairbanks Agriculture and Forestry Experiment Station, Palmer Soil and Plant Analysis Laboratory. Soil bulk density and water content were determined gravimetrically based on excavated volumes, weight, and weight loss of a subsamples dried to 105°C. Soil texture was determined by hydrometer method, pH by hydrogen ion electrode in a deionized water-saturated soil paste, and exchangeable acidity (H^+) by $BaCl_2$–triethanolamine leaching with HCl titration (Soil Survey Laboratory Staff, 1996). Total C and N were determined after ignition on a LECO 1000 CHN analyzer, inorganic C (IC) was determined by acidification of soil with 1M HCl, and measurement of carbon dioxide evolved by gas chromatography, with organic C taken as Total C minus IC. Available nitrogen (N) was calculated as ammonium N plus nitrate N extracted by 2M KCl (each determined colorimetrically), available P, K, Fe, and Zn were extracted by Mehlich 3 solution (Mehlich, 1984) and determined by inductively coupled plasma (ICP) spectroscopy. Soil cation exchange capacity (CEC) and exchangeable cations (K, Ca, Mg, and Na) were extracted with 1M-ammonium acetate pH 7 (Soil Survey Laboratory Staff, 1996) and determined by ICP spectroscopy. Water-soluble organic carbon was extracted from field-moist soil by 2:1 (volume: water to soil) 4-h equilibrium extraction followed by filtration through 0.45 μm pore membrane and dissolved OC determined on an OI Analytical TOC analyzer.

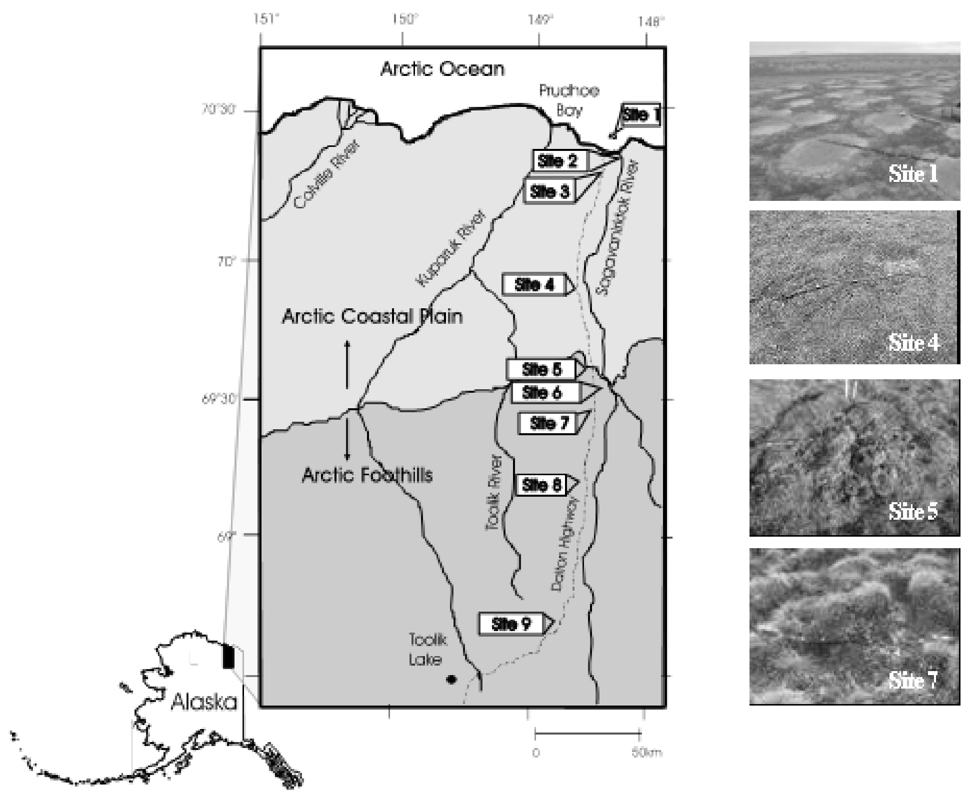

Fig. 1. Location of study sites (Site 1, Howe Island; Site 2, Endicott Road; Site 3, Deadhorse; Site 4, Franklin Bluffs; Site 5, Sagwon Hills moist nonacidic tundra; Site 6, Sagwon Hills moist nonacidic and/or acidic transition; Site 7, Sagwon Hills moist acidic tundra; Site 8, Happy Valley; Site 9, Dalton Highway Mile 294). Photos showing examples of frost boils from each region: the coast (Site 1), coastal plain (Site 4), foothills transition (Site 5), and foothills (Site 6). The tape shown in each photo is 2 m in length.

Total OC, N, and soil nutrient stock accumulations (in mass m^{-2}) were calculated using the sum of measured soil increment sample stocks calculated using field bulk density (BD), depth, and elemental analysis measurements (Michaelson et al., 1996).

RESULTS

Soils and Substrate Materials

Soils at the 10-cm depth are taken to most closely represent mineral soil substrates of the sites and their basic chemical characteristics of soil pH, acidity, Ca, Fe, IC, and OC (Fig. 2). Soil pH ranged from 8.5 at the northern coast to 5.0 on the southern foothills, while exchangeable acidity went from <1 to a high of 27 cmol H^+ kg^{-1} (Fig. 2a). Soil extractable Ca and exchangeable Fe followed pH and exchangeable acidity with Ca ranging from 14,170 mg kg^{-1} in the north to 110 mg kg^{-1} soil in the south, while Fe went from 70 to 822 mg kg^{-1} soil moving from north to south (Fig. 2b). The IC and OC followed similar north–south trends with an IC high of 3.0 g kg^{-1} in the north to near 0 g kg^{-1} at the southern sites and an OC of 24 g kg^{-1} in the north and increasing to 35 g kg^{-1} in the south (Fig. 2c). The OC contents were low with averages ranging from 19 to 44 g kg^{-1} and highly variable, and thus the trend across the study area was weak (ANOVA $p = 0.25$).

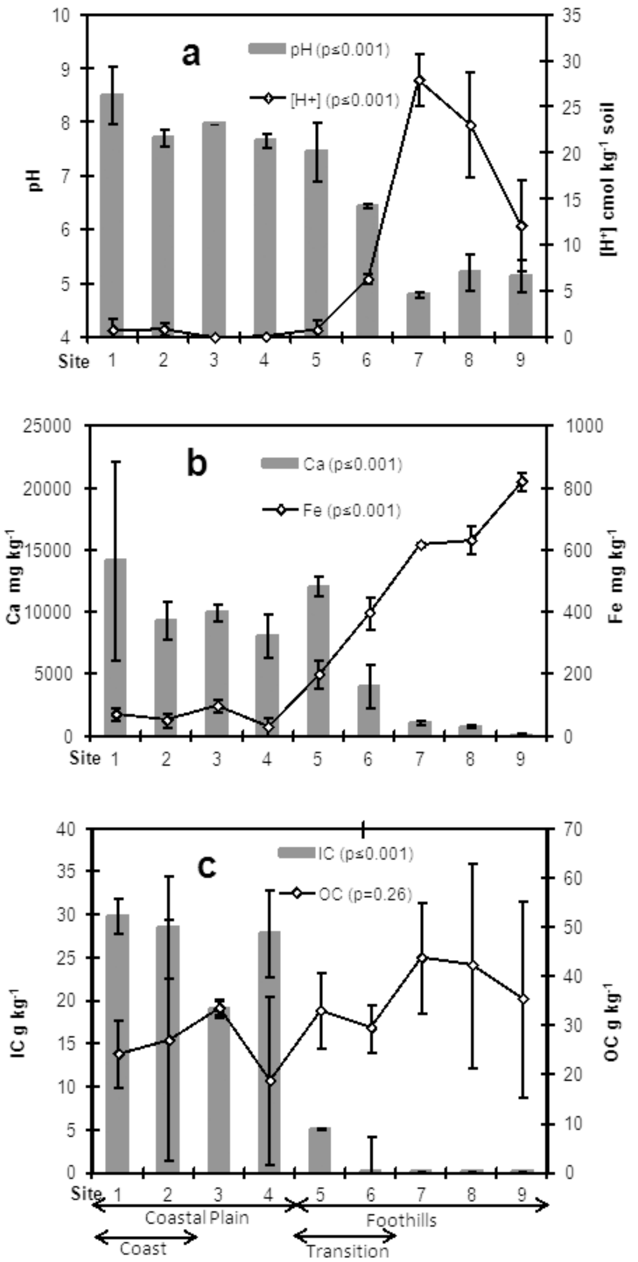

Fig. 2. Selected properties of mineral soil substrates at the 10-cm depth: (a) pH–acidity, (b) exchangeable Ca and available Fe, and (c) inorganic carbon (IC) and organic carbon (OC) levels across study sites from north to south (left to right). The p values in parentheses are from ANOVA for the means of each characteristic as they trend across the study area. The 95% confidence intervals of the bars and points are displayed with brackets.

Soil textures ranged from sandy loam and silt loam on the coastal plain to the north to silt loam, loam, and sandy clay loam in the foothills to the south (Table 1). In the nonacidic tundra of the northern study area, Haploturbels occurred on the drier sites (1 and 2) and Molliturbels or Historthels on the moist sites (Ping et al., 1998). Aquiturbels and Histoturbels occur at the southern end of the Transect under acidic tundra vegetation and moist conditions. Vegetation cover and life forms present were as typical for the tundra cover classes as described by Walker et al. (2011) (Table 1).

Soil Surface Properties

The uppermost 2 cm of mineral soil either reflects conditions of inherit chemistry of the mineral substrate or is most subject to changes due to either atmospheric exposure (for the bare condition), influence of biota or the atmosphere (crusted condition), or influences of OC accumulation and tundra plant establishment (vegetated condition). Table 2 presents selected properties of the uppermost 2 cm of mineral soil for each condition across the sites. Soil pH varied from 7.2 to 9.0 for the sodium-affected coastal sites to a more circumneutral 6.9 to 7.8 on the coastal plain, down to 6.2 to 7.4 for the transitional northern foothills, and then to an acidic 4.1 to 5.1 in the southern foothills. The OC, OCws, and total nitrogen (TN) generally increased with crusting and vegetation establishment over the bare condition ranging from 18 to 168 g kg^{-1} OC, 8 to 991 µg cm^{-3} OCws, and 1.0 to 6.4 g kg^{-1} TN. Inorganic C levels of the surface mineral soil layers ranged from 16 to 48 g kg^{-1} in the coastal and coastal plain sites, from <1.0 to 9.0 g kg^{-1} in the transitional foothills, and were all <1.0 g kg^{-1} for the foothill acidic sites. Extractable macronutrients ranged from <1 to 10 mg N kg^{-1}, <1 to 8 mg P kg^{-1}, and 17 to 282 mg K kg^{-1} across study sites and surface conditions. Base saturation (BS) status and soil total exchange acidity went from 100% BS and 0.1 to 5.8 cmol H^+ kg^{-1} in the coastal and coastal plain sites to 96 to 100% BS and 1.3 to 11.6 cmol H^+ kg^{-1} in the foothills transition, to 11 to 35% BS and 12.1 to 36.6 cmol H^+ kg^{-1} in the foothills sites. The BD of the surface mineral soil varied from 0.34 to 1.68 g cm^{-3}, generally decreasing with OC accumulation. Water contents varied widely across sites from 15 to 75%.

Soil Properties with Depth

Table 3 gives site averages within regions for CEC and distribution of major cations on the exchange. The CEC of soils

Table 1. Selected study site characteristics.

Site no., location, cover, and elevation†	Soil classification USDA	Surface frost boils‡ %	Soil texture USDA	Most common life forms and species
		Coastal		
1, Howe Is., DNT (1.5 m)	Aquic Haploturbels	73	Fine Sandy Loam	Polyblastia *sendtneri*, Leconora *epibryon*, Braya *purpurascens* (Crusts: primarily lichens)
2, Endicott Rd., DNT (1.5 m)	Aquic Haploturbels	75	Fine Sandy Loam	Dryas *integrifolia*, lichen species (Crusts: primarily lichens)
		Coastal Plain		
3, Deadhorse MNT (15 m)	Typic Histoturbels	24	Silt Loam	Eriophorum *triste*, Carex *membranacea*, D. *integrifolia*, Salix *arctica*, Tomentypnum *nitens* (Crusts: primarily lichens)
4, Franklin Bluffs, MNT–DNT(90 m)	Aquic Haploturbels	37	Fine Sandy Loam	D. *integrifolia*, Arctous *ruba*, T. *nitens* (Crusts: primarily lichens)
		Foothills Transition		
5, Sagwon MNT, (300 m)	Aquic Molliturbels	38	Silt Loam	Carex *bigelowii*, Eriophorum *vaginatum*, D. *integrifolia*, Salix *reticulata*, Hylocomium *splendens* (Crusts: primarily lichens)
6, Sagwon, MNT–MAT (300 m)	Aquic Molliturbels	25	Silt Loam	D. *integrifolia* (Crusts: moss–lichen mixture)
		Foothills		
7, Sagwon, MAT (300 m)	Ruptic-Histic Aquiturbels	5	Loam	E. *vaginatum*, Betula *nana*, Ledum *decumbens*, Vaccinium *vitis-idaea*, H. *splendens*, Sphagnum spp. (Crusts: moss–lichen mixture)
8, Happy Valley, MAT (320 m)	Ruptic Histoturbels	12	Loam	E. *vaginatum*, C. *bigeolwii*, B. *nana*, L. *decumbens*, V. *vitis-idaea*, H. *splendens* Sphagnum spp. (Crust: lichen, moss, cyano–bacteria mixture)
9, Dalton Hwy. Mi. 294, MAT (800 m)	Ruptic Histoturbels	5	Sandy Clay Loam	E. *vaginatum*, C. *bigeolwii*, B. *nana*, Sphagnum spp. Casiope *tetragonia* (Crust: filamentous blue-green algae)

† DNT, dry nonacidic tundra; MNT, moist nonacidic tundra; MAT, moist acidic tundra.

‡ Only frost boils apparent at the surface.

nearest the surface increased from bare to crusted to vegetated condition 11 to 20 cmol(+) kg^{-1}, 10 to 30 cmol(+) kg^{-1}, 21 to 39 cmol(+) kg^{-1}, and 17 to 55 cmol(+) kg^{-1} for the coast, coastal plain, foothills transition, and foothills regions, respectively. These increases in CEC for bare, crusted, and vegetated condition were lessened in the next layer sampled and disappeared within a few centimeters of the surface for all regions. Accumulation of the plant essential nutrients of K, Ca, and Mg displayed a similar pattern across the sites and regions, increasing at the surface and with crusted and vegetated condition. There was the opposite pattern for sodium concentrations of the coast and coastal regions. The surface layers tended to be highest in Na concentration for the bare areas and were decreasing in the crusted and vegetated surface layers 3.47 to 0.11 cmol Na kg^{-1} and 0.20 to 0.15 cmol Na kg^{-1} for the coast and coastal plain surfaces, respectively. This increased effect of Na under bare areas persisted to depth (10 cm sampled) for the coast sites but not the coastal plain sites. The Na concentrations for the foothills transition and foothills areas were markedly lower ranging from 0.02 to 0.012 cmol Na kg^{-1}, and there were no distinct patterns detectable among frost boil micro sites.

Organic Carbon Accumulation and Soil Properties

The distribution of soil properties and major nutrients with depth as summarized over sites of similar tundra types (nonacidic and acidic) are displayed in Fig. 3. Increased biotic activity on frost boils as indicated by a bare to crusted and then vegetated surface conditions resulted in an increased average surface accumulation of OC at 31, 29, and 166 g OC kg^{-1} for nonacidic sites and 61, 88, and 357 g OC kg^{-1} for acidic sites. Extractable acidity (H^+) followed a very similar pattern. Soil OC and H^+ were highly correlated with the nonacidic and acidic tundra soils following distinctly different trajectories for increasing acidity with increasing OC content (Fig. 4). However, the influence of OC on soil pH down into the profile tended to be more pronounced for the nonacidic sites than for the acidic sites with average pH for the bare crusted and vegetated profiles being 7.8, 7.6, and 7.3 compared to 4.8, 4.7, and 4.7 for the nonacidic and acidic profiles. Average CEC and extractable nitrogen (NH_4^+ and NO_3^-) phosphorus (P) and zinc (Zn), as well as soil BD all followed the depth-distribution patterns of OC distribution for the two tundra types (Fig. 3). Extractable iron (Fe) averaged higher for the acidic soils than the nonacidic soils at 587 and 105 mg Fe kg^{-1} over the depths of crust profiles with little variation from surface down the profile for either tundra type.

Table 2. Selected properties of surface mineral soils (0–2 cm) at each site.†

Site location no.	Boil microsite‡	pH	OC $g\ kg^{-1}$	OCws $mg\ cm^{-3}$	TN $g\ kg^{-1}$	IC $g\ kg^{-1}$	Extr. N $mg\ kg^{-1}$	Extr. P $mg\ kg^{-1}$	Exch. K $mg\ kg^{-1}$	BS %	H+ $cmol\ kg^{-1}$	B $g\ cm^{-3}$	$[H_2O]v$ %
						Coastal							
1	B	8.6	18	254	1.1	24	5	2	105	100	5.8	1.52	15
	C	9.0	37	953	2.6	30	8	5	207	100	1.9	1.05	46
	V	7.0	43	991	2.1	29	8	8	282	100	5.8	0.59	27
2	B	8.4	43	76	2.0	34	3	<1	101	100	0.1	1.30	48
	C	7.3	99	45	5.0	29	3	2	99	100	2.2	0.85	32
	V	7.2	168	40	5.7	23	3	7	122	100	3.6	0.45	16
						Coastal Plain							
3	B	7.7	48	31	1.8	18	6	1	56	100	1.1	1.52	60
	C	7.8	59	42	2.4	19	5	2	61	100	0.1	1.51	75
	V	7.6	96	112	4.0	16	7	6	126	100	2.3	0.63	58
4	B	7.4	19	21	1.6	41	1	<1	54	100	0.9	1.07	31
	C	7.2	66	27	5.2	48	5	<1	174	100	1.2	0.44	38
	V	6.9	129	56	6.4	28	3	3	205	100	4.2	0.38	35
						Foothills Transition							
5	B	7.2	39	9	2.8	9	2	1	137	100	1.7	0.39	18
	C	7.1	54	14	3.6	6	3	2	196	100	1.3	0.39	19
	V	7.0	135	40	4.8	7	3	5	206	100	8.1	0.66	39
6	B	7.4	29	9	2.2	2	1	1	101	100	2.2	0.84	20
	C	6.8	36	14	2.7	<1	<1	4	125	100	5.4	1.02	35
	V	6.2	60	28	3.2	<1	3	6	116	96	11.6	0.93	51
						Foothills							
7	B	4.8	40	19	2.1	<1	3	<1	111	31	21.7	1.14	50
	C	4.6	47	13	2.5	<1	7	<1	130	34	22.8	0.68	34
	V	4.1	83	37	3.3	<1	5	<1	132	14	33.4	0.88	57
8	B	5.0	45	13	1.8	<1	3	<1	122	35	23.0	0.80	41
	C	5.2	69	22	2.9	< 1	3	1	145	32	29.8	0.57	29
	V	4.9	111	40	4.9	<1	2	1	156	33	36.6	0.48	57
9	B	5.1	35	8	1.0	<1	7	<1	17	11	12.1	1.68	38
	C	5.3	55	23	2.2	<1	4	<1	135	26	13.9	1.24	31
	V	4.4	107	33	4.8	<1	10	<1	66	16	17.3	0.34	72

† Properties: OC, total organic carbon; OCws water soluble OC; TN, total nitrogen; IC, total inorganic carbon; Extr. N, total nitrate plus ammonium 2M KCl-extractable nitrogen; Extr. P, Mehlich 3 extractable phosphorus; Exch. K, ammonium acetate exchangeable potassium; BS, base saturation percentage; H^+, exchangeable acidity; BD, soil bulk density; $[H_2O]_v$, volumetric soil water content at sampling.

‡ B, barren; C, crust; V, vegetation mat.

DISCUSSION

Properties of Soils Substrates

Although soils at 10-cm depth are often B-horizon materials, they have properties more closely representing initial soil conditions for establishment of biota. These materials are frost heaved and have been brought to the surface in frost boil centers with minimal organic matter additions (Ping et al., 1998). Current biota must be able to establish on these soil materials as they are exposed at the frost boil centers. Sites 1 and 2 are near the Arctic Ocean shoreline (<1 km) and thus most directly influenced by sea salts, but all coastal plain sites to the south as well the northernmost foothills site 5 are in nonacidic relatively Ca-rich tundra soils. Nonacidic soils transition to acidic soils between sites 5 and 7 as the foothills rise to the older moraine surface (Fig. 1). The coastal plain consists of alluvium overlain by carbonate-rich loess blown in from the Sagavanirktok river floodplain (Walker and Everett, 1991). As the foothills rise on the southern border of the coastal plain, soils are better drained and soil parent materials are dominated by calcareous loess inputs only on the northernmost exposures or in positions immediately adjacent to large floodplains. Within a few kilometers to the south of the transition from coastal plain to foothills, parent materials become influenced by acidic glacial till overlain by and mixed with only minimal amounts of loess. Soils exposed in the centers of active frost boils reflect these parent material changes (Fig. 2). Soils at the 10-cm depth in the center of active boils have soil properties generally more similar to the subsurface horizons that extend deeper into the active layer (Ping et al., 1998). Bare soils exposed in frost boil centers are usually B- and C-horizons (Ping et al., 1998) that have been exposed to the surface by frost heave (Peterson and Krantz, 2008). In a north to south direction as the foothills rise from the coastal plain (Fig. 1), soil substrate pH crosses the neutral point (pH = 7.0) from alkaline to acid. This is evident between Sites 5 and 6 (Fig. 2a). At the same point in the transect the soil total exchangeable acidity rises from near zero to levels ranging from 12 to 27 cmol $H^+\ kg^{-1}$ soil in the MAT (sites 7–9). With the rise in acidity comes a decrease in soil extractable Ca and in-

Table 3. Exchange capacity and cation status of frost boil surface soils at incremental depths (0–10 cm under bare [B], crusted [C], and vegetation mats [V] on frost boil centers) averaged for the two sites from each region of the study transect.

Depth Increment†	Cation exchange capacity $cmol_c\ kg^{-1}$			K $cmol\ kg^{-1}$			Ca $cmol\ kg^{-1}$			Mg $cmol\ kg^{-1}$			Na $cmol\ kg^{-1}$		
	B	C	V	B	C	V	B	C	V	B	C	V	B	C	V
Coast DNT (*n* = 2) ‡															
1	11	15	20	0.26	0.39	0.52	35	65	67	4.3	3.4	2.4	3.47	1.84	0.11
2	9	12	12	0.24	0.28	0.34	37	65	62	3.6	2.8	2.4	2.83	1.81	0.14
3	8	11	14	0.19	0.27	0.23	37	100	71	3.5	3.1	2.6	2.22	2.08	0.23
4	7	16	9	0.16	0.15	0.16	38	76	78	3.0	2.5	2.8	1.30	1.12	0.31
5	5	12	9	0.13	0.14	0.16	36	73	78	2.4	2.3	2.8	0.97	1.08	0.31
Coastal Plain MNT (*n* = 2)															
1	10	16	30	0.14	0.30	0.42	49	58	79	3.0	2.5	3.2	0.20	0.15	0.15
2	7	9	14	0.07	0.10	0.11	48	50	54	1.5	1.3	1.5	0.11	0.09	0.12
3	9	8	11	0.06	0.06	0.07	50	46	51	1.2	1.0	0.9	0.10	0.08	0.08
4	10	7	9	0.06	0.05	0.05	47	41	45	1.1	0.8	0.8	0.09	0.08	0.09
5	9	8	9	0.05	0.04	0.05	48	39	48	0.9	0.7	0.7	0.09	0.08	0.08
Foothills Trans. MNT–MAT (*n* = 2)															
1	21	26	39	0.31	0.47	1.25	44	44	91	5.8	5.2	9.2	0.07	0.07	0.12
2	23	24	29	0.23	0.23	0.31	39	42	44	4.8	4.2	4.6	0.05	0.06	0.06
3	22	22	23	0.19	0.17	0.23	45	28	42	4.0	3.4	4.2	0.05	0.05	0.05
4	25	23	23	0.16	0.15	0.19	42	42	41	3.5	3.0	3.6	0.05	0.06	0.05
5	25	23	23	0.16	0.15	0.18	42	42	36	3.3	3.0	3.4	0.05	0.05	0.05
Foothills MAT (*n* = 2)															
1	17	30	55	0.54	0.52	1.38	6	6	21	1.3	1.4	3.6	0.07	0.03	0.10
2	17	22	30	0.16	0.19	0.28	4	3	7	0.7	0.9	1.4	0.03	0.03	0.05
3	20	23	18	0.12	0.11	0.09	4	4	5	0.8	0.8	1.1	0.04	0.03	0.02
4	23	24	21	0.07	0.10	0.07	4	4	5	0.8	0.9	1.2	0.04	0.03	0.02
5	21	27	22	0.06	0.06	0.06	4	5	6	0.9	1.0	1.3	0.04	0.04	0.03

† Tundra cover type: DNT, dry nonacidic tundra; MNT, moist nonacidic tundra; MAT, moist acidic tundra.

‡ Increment 1 was the surface crust thickness and varied from 0.5–2 cm thickness for bare and crusted areas, while the organic surface soil layer was sampled as increment 1 for the vegetated areas varying from 1–4 cm thickness. Under increment 1 soils were sampled at 2 cm thickness interments to a total depth of 10 cm.

crease in available soil Fe (Fig. 2b). Such a trend has been attributed to more leaching due to increasing precipitation and less calcareous loess inputs from the north to south (Ping et al., 1998). Along this study transect north to south there is also a climate gradient of increasing temperatures (mean annual air temperature: −12.5 to −11°C) and precipitation (annual: 125 to 270 mm) that follows elevation (Table 1) from sea level to about 1000 m (Zhang et al., 1996). Soil carbonate or inorganic carbon (IC mostly in the form of calcium carbonate) follows the same pattern as pH across the study sites (Fig. 2c). Organic carbon in soil substrates at the 10-cm depth, although lower in magnitude, was highly variable across all sites and only weakly trended higher in the MAT foothills sites relative to the other soils. However, the average OC of the acidic sites 40 g kg^{-1} was significantly higher (*t* test $p = 0.04$) than the nonacidic sites 28 g kg^{-1}. An older soil–landscape age for the southern foothills with more time for mixing, weathering, biological activity, and leaching of the soil is likely responsible for the raising trend for overall substrate OC as well as Fe and acidity levels in the mineral subsurface soils. Surfaces of the MAT are older, dating from early to mid-Pleistocene, whereas the MNT of the northernmost foothills and coastal plain are predominately Holocene deposits (Hamilton, 1987). The generally higher OC and Fe and lower Ca levels found in these MAT soils that are potentially exposed at the surface of active frost boils is likely an important factor in determining the different type and degree of crusting that can develop relative to the Ca-rich lower OC nonacidic soils.

Crusts, Vegetation, and Soil Properties

The most apparent effects of soil biotic crusts were trends of increased soil OC and TN in the mineral soils of crusts and in the uppermost mineral layers of soils immediately underlying the organic surface layers of vegetated areas when compared to the bare surface soils (Table 2). Water-soluble organic carbon and nutrient levels (extractable N, P, and K) also tended to be higher at most sites with crusting or vegetation establishment, but the trend was not consistent across all frost boils. When soil pH levels of crusted and vegetated areas are compared to adjacent bare areas, pH levels were generally lower with increased exchangeable acidity (H^+) and decreasing BD as OC accumulates. Sites on the coastal plain nonacidic tundra and foothills acidic and/or nonacidic transition (Sites 1–6) were higher in carbonates (IC) and tended to buffer a pH drop and total acidity (Fig. 4) that would come as a result of proton release with biological activity. Soil substrates of the northern regions having high IC content from calcareous-loess parent materials served to moderate the potential decrease in pH with increased OC levels. Therefore, crust soils had intermediate OC

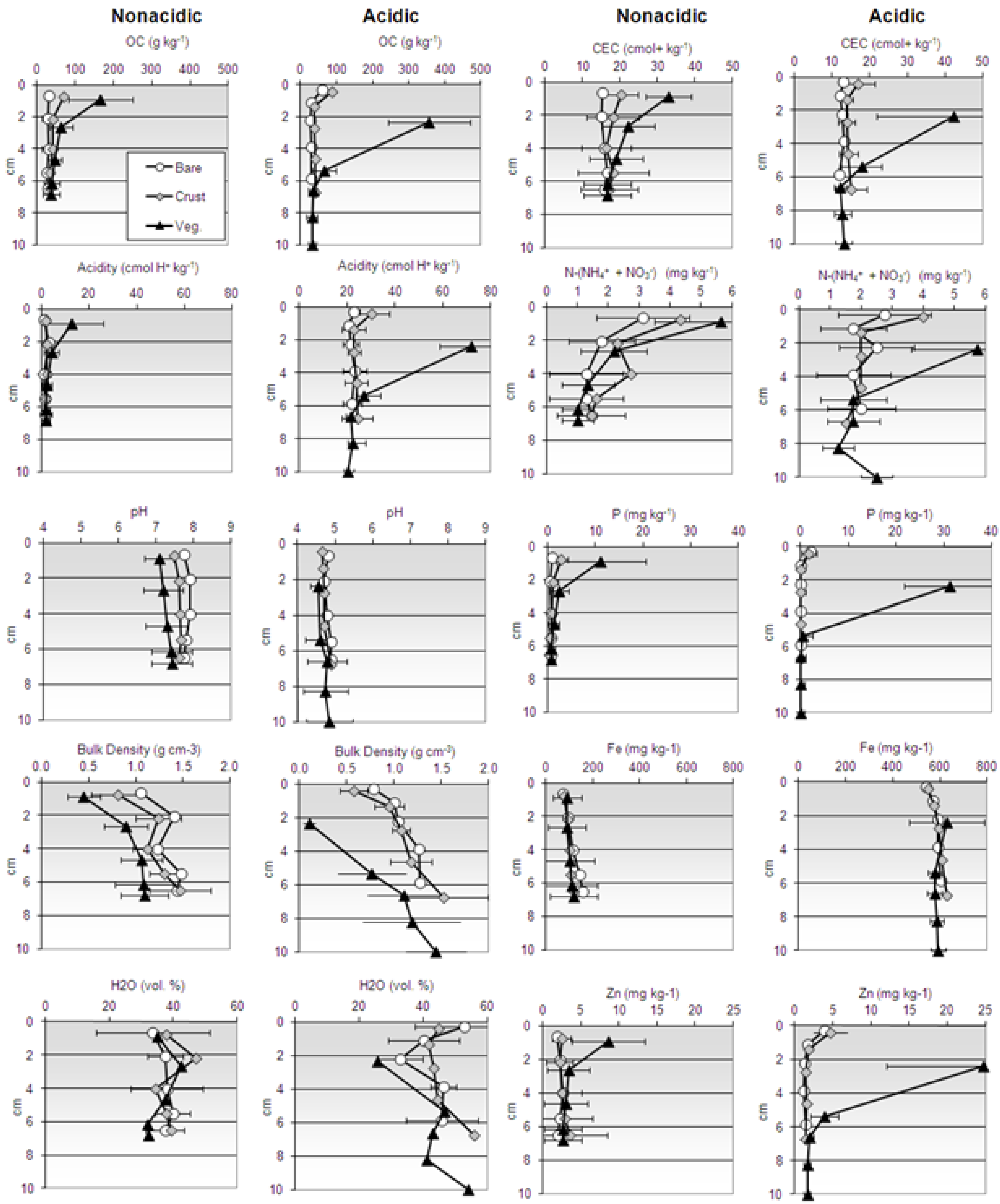

Fig. 3. Selected average soil properties of the surface depth profile under the bare, crusted, and fully vegetated areas within frost boils from nonacidic (average Sites 1–6) versus acidic sites (average Sites 7–9). Bars represent the 95% confidence interval.

levels between the bare and vegetated soils but they were not necessarily intermediate in pH. These observed differences in soil chemistry response to OC accumulation between acidic and nonacidic soils likely is an important factor in establishment of varying plant communities as exposed soils form biotic crusts and revegetate. The acidic materials increase in acidity while nonacidic materials experience little change in soil reaction. Soil pH was above 8 for the two coast sites (sites 1 and 2) likely due to elevated sodium (Na) levels from sea-salt influence in the surface of bare soils (Tables 2 and 3). In the carbonate-rich coastal and transition sites IC would be expected to moderate pH with proton production. For the Na-rich coastal sites, Na accumulation would be expected to elevate pH. These effects were observed over the range of these substrates and could affect vegetation establishment and composition as well as in the case of Na rich surface areas aid in the persistence of bare areas on frost boils.

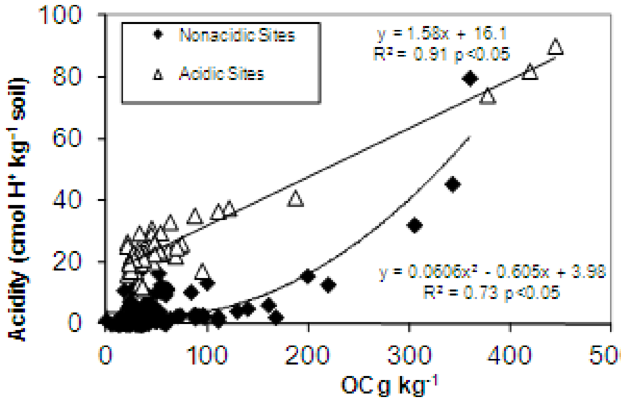

Fig. 4. Soil acidity (soils from all 0- to 10-cm depth increments) and carbon content for nonacidic (Sites 1–6) versus acidic sites (Sites 7–9).

Surface Na levels for Sites 1 and 2 were 2.8 and 4.1 cmol Na^+ kg^{-1} soil, respectively. Sodium levels decreased with distance of sites from the coast to levels of 0.3 cmol Na^+ kg^{-1} soil at site 3 (5 km inland), and all other sites were ≤0.1 cmol Na^+ kg^{-1} soil (Table 3). The crusted surface at site 1 had the highest pH (9) and the highest Na levels: 3.5 cmol Na^+ kg^{-1} soil. Surfaces dominated by calcium carbonate were rough probably due to the disruptive effects of needle ice formation in the fall interacting with the aggregating effects of calcium. The Na-affected bare surfaces of sites 1 and 2 were relatively smooth, firm, and slick when moist with hexagonal surface freeze-drying expansion cracks present (Drury, 1962). The difference in cation species balance for these physically crusted bare surfaces is likely due to the dispersing soil-sealing effect of Na (Brady and Weil, 1999) on the soil bare surface (coast sites) and calcium having an opposite soil-aggregating effect (coastal plain and foothills transition sites).

The CEC for soils under bare and crusted surfaces was generally lower on the coastal plain, about half compared with the foothills soils (Table 3.). These observations are consistent with the general change in soil texture with increased proportions of clay and reduced proportions of sand on the older glacial drift surfaces of the foothills relative to the younger alluvial coastal plain surface (Ping et al., 1998; Hamilton, 1987). The presence of a vegetation mat or crust was associated with increased CEC across the regions. Crusts affected soil CEC to a lesser depth than did vegetation mats (Fig. 3 and Table 3). Organic matter has been shown to be the primary contributor to CEC for these soils and is likely to be primarily responsible for variation in CEC along with a lesser effect of clay (Ping et al., 2005). Over all of the sites the presence of vegetation mats significantly increase surface layer CEC over that of bare and crusted conditions (Table 3 and Fig. 3). Crust CEC tended to be higher than bare but was very similar in range. This trend is consistent with the greater nutrient bioaccumulation and increased organic matter in soils. Accumulations of various species of cations, however, did not necessarily follow CEC with different trends in cation accumulations with different site substrate chemistries (Table 3). The nonacidic tundra and transition sites had high overall basic cation levels with more of an incremental increase observed under crusting and then vegetation mats. The less abundant and more soluble cations potassium, sodium, and magnesium were higher in surface layers of all bare soils, which is consistent with surface accumulation of cations aided by capillary transport and then evaporative deposition at the bare soil surface, a process that could be expected to be higher for bare areas relative to the more surface-protected crust and vegetated areas of frost boils.

Calcium is abundant throughout the coastal plain and foothills transition surface soils. Levels of Ca tended to be higher near the surface under crusts and vegetation mats (Table 3). The coast sites near the ocean (Sites 1 and 2) had the same pattern of high Ca under crusts and vegetation mats relative to bare areas, but they also had markedly higher sodium levels, especially in the bare surface layers. The bare areas from coastal sites had calcium levels that were about half those of the adjacent soils under crust and vegetation mats. The surface layer of the bare soils in coastal sites had Na/CEC (0.32) and pH levels (>8) characteristic of saline-alkali soils and (U.S. Salinity Laboratory Staff, 1954) with only halophytic plants establishing themselves on bare sites (D.A. Walker, unpublished data, 2001).

Soil OC of the surface mineral layer of crusted areas was intermediate between adjacent bare and vegetated areas (Table 2). There was little OC or H^+ enhancement below 2 cm (first increment of sampling) for the crusts or even below the vegetation mat areas themselves (Fig. 3). Nutrient holding capacity as indicated by CEC followed this same pattern as did extractable N, P, and Zn. Extractable Fe levels were different between acidic and nonacidic sites but showed little variation with depth (Fig. 3). In contrast to OC, soil BD tended to increase with depth. This could be indicative of the combined influence of OC enhancement and physical disruption of frost at the surface increment and soil compaction influences increasing with depth in the mineral soil. Vegetated areas tended to have lower BD than crusted or bare areas, especially for the acidic sites. This is also consistent with soil being more physically protected or stabilized under vegetation relative to that under the more exposed crusted or bare areas. Volumetric water contents with depth were variable across the sites (Fig. 3). Precipitation is low across the study area grading from 125 mm in the north to 270 mm in the south (Haugen, 1982) with about half falling as snow. These relatively dry conditions increase the significance of surface cryptogam cover to the dynamics of heat transfer (Gold, 1998) surface wetting, drying and infiltration characteristics, and availability of soil water and its solutes (Gold and Bliss, 1995). Crusts tended to preserve surface moisture relative to vegetated areas for the dryer sites for the coastal plain (Table 2, Sites 1–4), while in the wetter foothills (Sites 4–9) surface moisture under vegetated areas tended to exceed that of the crusts. This could be due to differences in evapotranspiration, vegetative transpiration and/or the effects of physio-chemical crusting (surface salt accumulation) that are more pronounced for the nonacidic carbonate-rich coastal plain soils.

Within individual boils at sites (Table 2), crusts tended to enhance the properties associated with increased soil fertility and nutrient holding capacity over that of the bare situation. Soil properties most affected by crusts were those associated with OC enhancement and nutrient buildup in an increased soil organic pool size. Most affected by this buildup were the surface few centimeters, where conditions would be critical for plant establishment (Bliss and Gold, 1999).

Organic Carbon Accumulation and Soil Properties

As organic matter accumulates, decomposition produces organic acids that can alter soil properties, especially soil pH. In arctic Alaska ecosystems soil pH is known to be a primary factor associated with trace-gas flux, plant community composition, animal habitat suitability, and overall ecosystem function (Walker et al., 1998). The acid-buffering capacity of soil carbonates as indicated by the inorganic carbon content of soils (Fig. 2c) is important to the nature and degree of soil reaction change that can occur with the OC accumulation and decomposition that comes with the establishment of crusts or vegetation. In the northern study area (Sites 1–4), substrates were rich in acid-neutralizing carbonates as indicated by high IC content. The IC present in this area is largely in the form of calcium carbonates from limestone-rich loess (Hamilton, 1987; Walker and Everett, 1991). Soil IC levels were reduced, and soil substrate pH was near neutral in the northern foothills (Sites 5–6) where soils transition from non-acidic to acidic (north to south). Soil IC is very low in the southern foothills (Sites 7–9) with acidic pH conditions. In general, there is a buildup of OC in subsurface mineral soils moving from the northern coastal to southern foothills areas (Fig. 2c). The relationship between acidity (H^+ produced by OC decomposition) and OC present in soils was linear on acidic sites where IC content is very low and nonlinear for soils of the nonacidic sites with their high IC contents available to neutralize the acids produced (Fig. 4). The relationships for soil H^+ as a function of OC indicates that acidity produced from organic matter decomposition is effectively buffered with the accumulation of up to nearly 200 g kg^{-1} OC for the nonacidic soils (Sites 1–6). The degree of mixing through cryoturbation and extent of decomposition with time also will be important factors along with bioaccumulation of OC and IC loess inputs in affecting soil substrate pH changes over the long term. In the nonacidic soils of the north, pH differences observed between soils of surface bare versus crusted condition were apparently more affected (elevated) by translocation of Na and Ca salts in the surface of soils masking any detectable H^+ changes in acidity that may be produced by organic acids in the vegetated condition (Table 2). Effects of acid production on pH were most apparent under vegetation mats of the acidic foothills sites where IC was low and OC accumulation highest.

Water-soluble organic C can be expected to increase with biological activity because it not only contains highly bioavailable organic substrates for microorganisms but the OCws itself is a product of biological activity or decomposition of organic matter (Whittinghill and Hobbie, 2011; Michaelson and Ping, 2003; Hurst, 1985). In nonacidic mineral soils (Fig. 5a) OCws stocks are more closely related to soil total OC stocks (R^2 = 0.62) than soil N stocks (R^2 = 0.19, data not shown). Whereas for the acidic soils (Fig. 5b), OCws stocks are more closely related to soil N stocks (R^2 = −0.69) than OC stocks (R^2 = −0.58, data not shown). These variations were seen in the farthest north nonacidic site 1 (Fig. 5a) and for acidic mossy Site 8 (Fig. 5b). In both cases lower soil temperatures could be partially responsible for these soils retaining high OCws levels through its controlling effects on soil microbial activity (Michaelson and Ping, 2003). At Site 1 the high Na-salt concentrations could also influence microbial activity.

Soil extractable nutrient levels varied widely across study sites and no significant relationships were found for nutrients and other soil properties (data not shown). But within sites, and on individual frost boils, nutrient levels were related to soil OC content and in some cases OC quality as indicated by C to N ratios (Table 4). Soils of nonacidic coastal plain, transition foothills, and acidic foothills soils are represented by Sites 3, 5, and 8, respectively (Table 4). Each site showed significant relationships for soil extractable nutrients N, P, K, Ca, and Mg as a function of soil OC content. Soil OC quality as indicated by soil C to N ratios (C/N) related well to extractable macronutrients for the transition and acidic foothills sites, but the nonacidic coastal plain site showed no relationship between C/N and soil nutrients. This could indicate and is consistent with C/N ratios

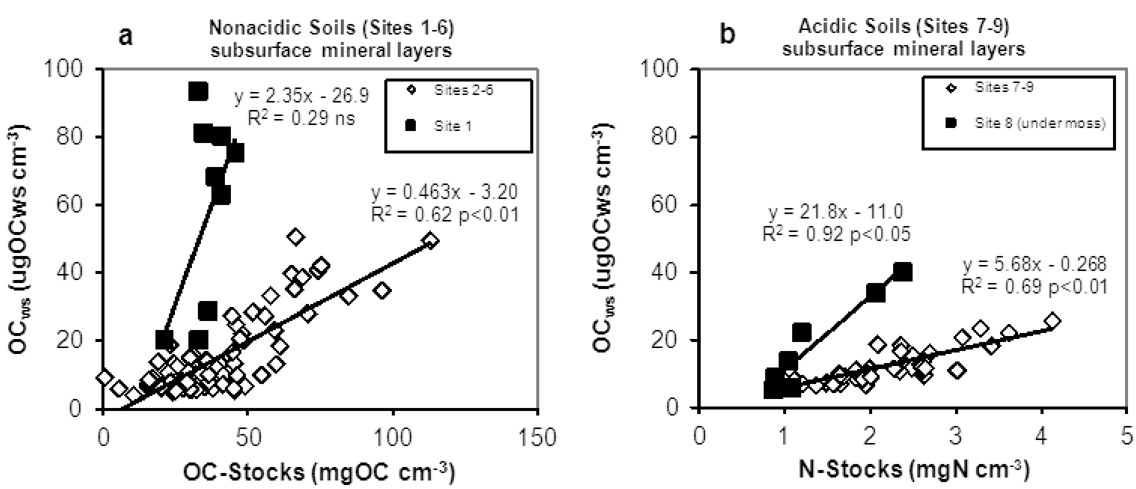

Fig. 5. Soil stocks of water-soluble organic carbon (OCws) and total (a) organic carbon (OC) stocks for nonacidic sites and (b) soil N stocks for acidic sites.

being lower for the northern nonacidic sites in general and nitrogen not playing as significant a role in controlling overall nutrient availability there compared to acidic sites to the south.

Table 4. Regression coefficients (R2) for soil 2M KCl extractable nitrogen and Mehlich 3 extractable nutrients with levels of total soil organic carbon (OC) and OC to total nitrogen ratios (C/N).

Extractable Nutrient	Coastal Plain Nonacidic Site 3 (n = 15) OC	Coastal Plain Nonacidic Site 3 (n = 15) C/N	Foothills Transition Site 5 (n = 18) OC	Foothills Transition Site 5 (n = 18) C/N	Foothills Acidic Site 8 (n = 50) OC	Foothills Acidic Site 8 (n = 50) C/N
N	0.61***	0.20	0.69***	0.62***	0.61***	0.30***
P	0.75***	0.20	0.90***	0.90***	0.96***	0.54***
K	0.84***	0.11	0.85***	0.81***	0.94***	0.53***
Ca	0.72***	0.19	0.70***	0.69***	0.96***	0.50***
Mg	0.74***	0.10	0.50**	0.46**	0.76***	0.53***

** Significance: $p < .01$.
*** Significance: $p < .001$.

Average soil surface layer stocks of extractable and/or available nutrients and total OC and N are given in Fig. 6. In general, for the crusted condition, nonacidic soils contained higher nutrient levels than for the acidic crusted soil condition. The t test differences for the means of OC, P, and K stocks for the crusts from the nonacidic versus acidic were significant to the $p \leq 0.06$ level. However, for the vegetated condition, acidic sites were highest averaging 34% more OC accumulated, 69% more available P, and 47% more available K compared to the vegetated nonacidic sites. But variability was higher and the t test differences for the means of OC, P, and K stocks for the vegetated condition from the nonacidic versus acidic were significant to only the $p \leq 0.25$ level. The lower C/N of the nonacidic sites indicates that they contain organic matter (OM) of higher quality than corresponding acidic sites with a trend of decreasing OM quality with increasing OC stocks among the frost boil surface types of both acidic and nonacidic sites. There tended to be a higher accumulation of OC for the vegetated frost boil micro sites on acidic soils compared to vegetated nonacidic sites, but N stocks were lower. This is consistent with the differences in C and N cycling that has been observed for nonacidic versus acidic tundra cover types in general (Walker et al., 1998; Hobbie and Gough, 2002) and with trends found for surfaces of increased age (Whittinghill and Hobbie, 2011). However, the higher relative nutrient levels, OC, and N stocks of bare and crusted surfaces of nonacidic soils relative to acidic soils have not been fully studied. Presumably higher-quality plant matter and soil OM inputs from the nonacidic relative to the acidic tundra vegetation communities (Walker et al., 1998) over time combined with lower temperatures in the more northern nonacidic sites are at least partially responsible for this relationship. Hobbie and Gough (2002) found that the nutrient status of the vegetation was higher and reflected higher soil available nutrients when comparing localized nonacidic and acidic tundra sites near Toolik Lake just to the south of sites in this study. Different nutrient contents for the same plants growing on nonacidic versus acidic soil were noted by Bockheim et al. (1998). Higher available P stocks for the acidic vegetated surface micro sites is in contrast to results reported in the Toolik Lake acidic versus nonacidic tundra study and may reflect differences brought about through successional changes in acidic tundra from initial vegetation mat establishment to a stabilized organic layer development. Higher available P for mineral nonacidic soils compared to acidic mineral soils is similar to the findings of Walker and Everett (1991) who contrasted calcareous loess deposits of the northern study area with acidic soils of the region. However, bioaccumulation of nutri-

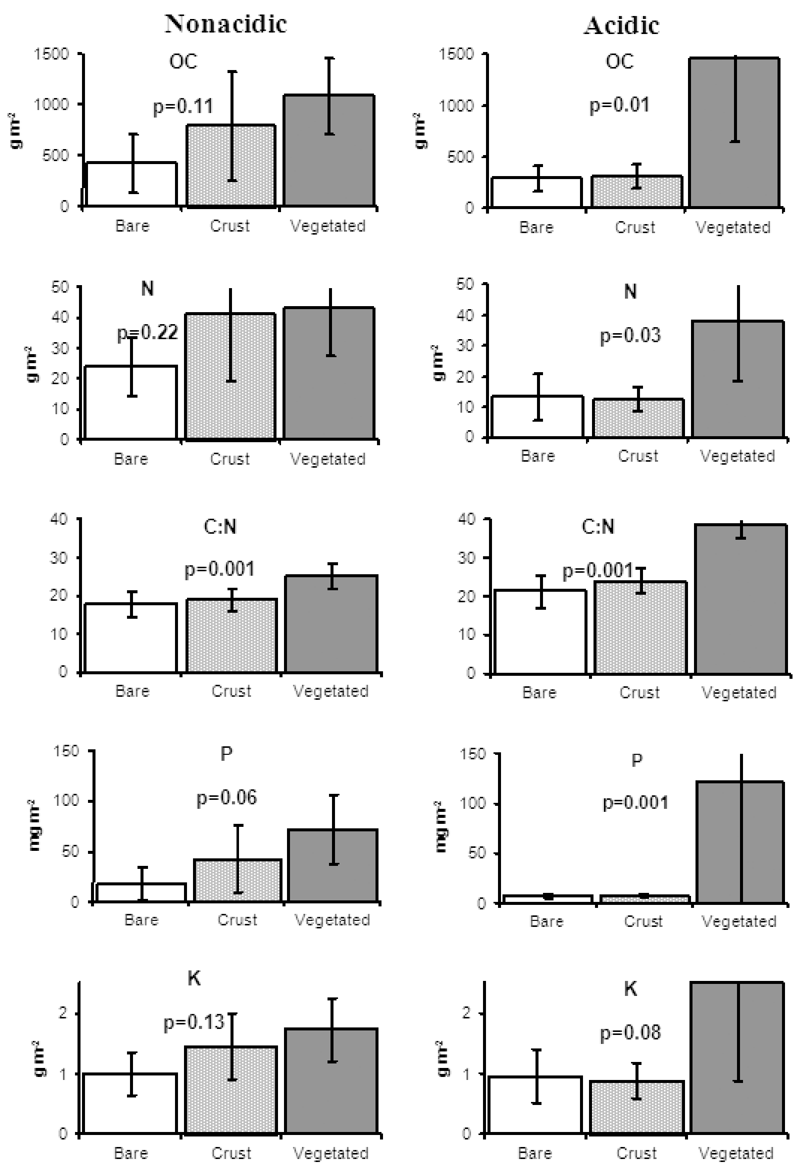

Fig. 6. Average total stocks for soil surface layers of total C and N and available P and K (Mehlich 3 extractable) accumulated for frost boil surface layers at nonacidic (Sites 1–6) and acidic sites (Sites 7–9). The p-values given are from ANOVA for surface condition means over the nonacidic and acidic sites. Average surface layer depths for nonacidic sites bare, crust, and vegetated were 1.3, 0.6, and 1.5 cm and for acidic sites 0.9, 1.8, and 4.8 cm, respectively.

ents in crusts and vegetation mats appears to be an especially important factor that increases stocks of available nutrients for the nonacidic and acidic soils, respectively. In addition, the concentration of available nutrients is limited to relatively thin layers within the surface few centimeters of soil. These bioaccumulations can overshadow even basic soil substrate differences and reverse the relative P and K nutrient stock status of acidic versus nonacidic tundra with crust formation in nonacidic soils and the accumulations of OM in vegetated acidic tundra boil micro sites.

CONCLUSIONS

In addition to the physical hydrothermal effects on soil of biota establishment found by others (Kade and Walker, 2008; Gold, 1998), our results indicate that crusting and vegetation of frost boil centers results in soil chemical changes that vary as soil substrate chemistry changes across northern Alaska from the coast to foothills of the Brooks Range. At the coast salt accumulation at the surface is apparent for both crusted and bare soils. Soil substrates of the coastal areas can be expected to have higher sodium salts with surface accumulation in bare areas of frost boils. The levels of accumulation are high enough to affect soil–plant water relations and soil structure, thus plant species and seedbed suitability. Calcium on the other hand can become depleted under the bare areas and enriched under crusts and vegetated areas of boils. This could serve to preserve plant species diversity and encourage the maintenance of surface patterns of vegetation and circles presumably even with the cessation of frost boil physical activity. Crusts developed on boils with Ca-rich (nonacidic) substrates as those found on the coastal plain accumulate Ca salts at the surface of the crust and in areas with vegetation cover, whereas the bare areas of the boil show even distribution of Ca near the surface consistent with more active mixing at the surface due to seasonal frost processes. As a result of the differences in substrate chemistry and salt species distribution, physical properties of the boil bare areas are likely impacted. The maintenance of bare areas is favored, and biological crusting could be deterred as a result of their susceptibility to repeated seasonal disruption of ice crystal formation.

Overall the most important effects of crust and vegetation cover establishment may be those effects affecting soil fertility. These effects result from the accumulation of organic C and N, acidity, and nutrients in the soil system. Although these effects most immediately affect only a relatively shallow depth of centimeters or less, in the short term they are important to plant establishment and biological activity, and over the longer term with cryoturbation will likely affect the entire active layer. Soil properties are affected through the accumulation and cycling of OC in the system. An important direct and immediate result of soil organic matter cycling in crusts is the release of protons increasing soil acidity. As climatic conditions change if there is a cessation of frost boil activity and an organic matter buildup on the surface of boil centers, then it could be expected that there will be an increase rate of soil acidification and subsequent changes in plant communities. This would happen more rapidly in the transition areas between coastal plain and foothills and areas distal to carbonate inputs from loess sources. Soil properties are affected differently by proton release according to the character of soil substrates. In the calcium carbonate–rich substrates (of the northern study area), acidity is buffered and nutrients such as phosphate are released as the organic nutrient pool is increased. In acidic substrates of the southern foothills area, acidity of the surface mineral soil builds up along with the nutrient pool in the organic layer. In all soils organic matter greatly increases the soil's ability to hold biologically available nutrients. In the soils from more temperate regions, these processes work primarily from the surface down with a static-horizontal layering of soil horizons. But for the tundra frost boil system, over a longer time the affected surface soils and their nutrient pools are physically mixed to depth (down as far as the top of the permafrost table) eventually affecting the physiochemical dynamics of the whole active layer and upper permafrost. The longer-term mixing of nutrient and carbon-rich surface soils to the lower active layer and upper permafrost contribute to the favorable conditions for late season and early winter soil respiration at depth, a process that is likely to increase tundra ecosystem respiration with warming climate.

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