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Soils and Cryoturbation in Moist Nonacidic and Acidic Tundra in the Kuparuk River Basin, Arctic Alaska, U.S.A.

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Abstract

We compared 22 pedons derived from silty materials in moist nonacidic tundra (MNT) and moist acidic tundra (MAT) in the arctic foothills of the 9200-km^2 Kuparuk River basin in northern Alaska. Soils in MNT have thinner organic horizons, a significantly thicker active layer, and greater cryoturbation than soils in MAT. The quantities of clay and organic-plus-inorganic C in the upper 100 cm are comparable; however, soils in MNT have significantly greater amounts of extractable Ca, Mg, and sum of base cations and significantly lower amounts of exchangeable acidity and Al than soils in MAT. Tissues from forbs, sedges, and woody shrubs in MNT have two to three times as much Ca as the same or similar species in MAT. The area of nonsorted circles was significantly greater in MNT (9.6%) than in MAT (0.9%). Although the existence of nonacidic tundra in the Arctic has been known for some time, its origin and distribution have not been fully explained. Our data link soil and vegetation properties and indicate that cryoturbation plays an important role in maintaining MNT in arctic Alaska.

Introduction

Moist nonacidic tundra comprises nearly half (45%) of the 9200-km^2 Kuparuk River watershed (Auerbach et al., 1996). Although physiognomically similar, moist nonacidic tundra and moist acidic tundra have different vegetational composition, soils, thawing depth of the active layer, and land-atmosphere exchange of energy and trace gases (Walker and Acevedo, 1987; Walker and Everett, 1991; Walker et al., 1994; Shippert et al., 1995; Walker et al., 1995; Nelson et al., 1997).

Douglas and Tedrow (1960) were the first to report calcareous tundra soils in northern Alaska. Soils adjacent to the Sagavanirktok River were consistently alkaline. Calcareous soils derived from loess and lacustrine materials occur throughout the Prudhoe Bay region (Everett, 1975; Everett and Parkinson, 1977; Parkinson, 1978). Walker and Everett (1991) collected soil samples along a 20-km loess gradient downwind of the Sagavanirktok River, showing the effects of loess deposition on particle-size distribution, pH, and other soil properties. They proposed that early minerotrophic stages of tundra succession in northern Alaska are maintained by loess blown off the Sagavarnirktok, Canning, and other large braided rivers.

The mechanism for soil acidification on loess-derived soils in the arctic foothills is not completely understood. Past studies suggest that plant succession plays a large role in the distribution of moist nonacidic and moist acidic tundra (Walker et al., 1995; Walker and Walker, 1996).

This study compares and contrasts silt-rich soils under moist nonacidic tundra and moist acidic tundra over a much larger area than previous studies and illustrates the importance of cryoturbation in maintaining moist nonacidic tundra. The contribution is part of the Arctic Flux Study, an investigation into land-atmosphere-ice interactions in arctic Alaska (Weller et al., 1995).

Methods and Materials

EXPERIMENTAL SITES

Fieldwork was conducted in and near the 9200-km^2 Kuparuk River watershed (Fig. 1). Pedons were described and sampled in the arctic foothills (17 sites), the arctic coastal plain (4 sites), and the Brooks Range (1 site). The study area is within the zone of continuous permafrost (Péwé, 1975). Active-layer thickness over the study area averaged about 44 cm in 1995 and 1996 but varied substantially with surface and substrate properties (Nelson et al., 1997; 1998). Elevations range from 1150 m in the southern foothills to sea level at Prudhoe Bay.

Climate in the area varies with distance from the Arctic Ocean and with elevation. Mean annual air temperature ranges from -12.8°C at Prudhoe Bay to -5.9°C in the Brooks Range (Haugen, 1982). Temperature extremes are greater in the Brooks Range and arctic foothills than in the arctic coastal plain. Precipitation along the gradient decreases northward from 300 to 450 mm yr^{-1} in the Brooks Range to 180 to 230 mm yr^{-1} in the arctic coastal plain.

The major landcover classes in the Kuparuk River basin (Fig. 1) (including percentage of area) are moist nonacidic tundra (45%), moist acidic tundra (25%), and shrublands (18%), with lesser amounts of wet tundra (6%), barrens (1%), and open water (5%) (Auerbach et al., 1996). Some of the shrublands are nonacidic (Bockheim et al., 1997).

Moist nonacidic tundra is composed primarily of nontussock sedges (*Carex bigelowii* Torr. and *Eriophorum triste* [Th. Fries] Hadoc & Love), a few prostrate shrubs (*Dryas integrifolia* M. Vahl, *Salix reticulata* L. ssp. *reticulata,* and *S. arctica* Pall.), and brown mosses (*Tomentypnum nitens* Hedw. and *Hylocomium splendens* [Hedw.] Schimp.). In contrast, the moist acidic tundra contains cottongrass tussocks (*Eriophorum vaginatum* L.), dwarf-birch (*Betula nana* L. ssp. *exilis* [Sukatsch.] Hult.),

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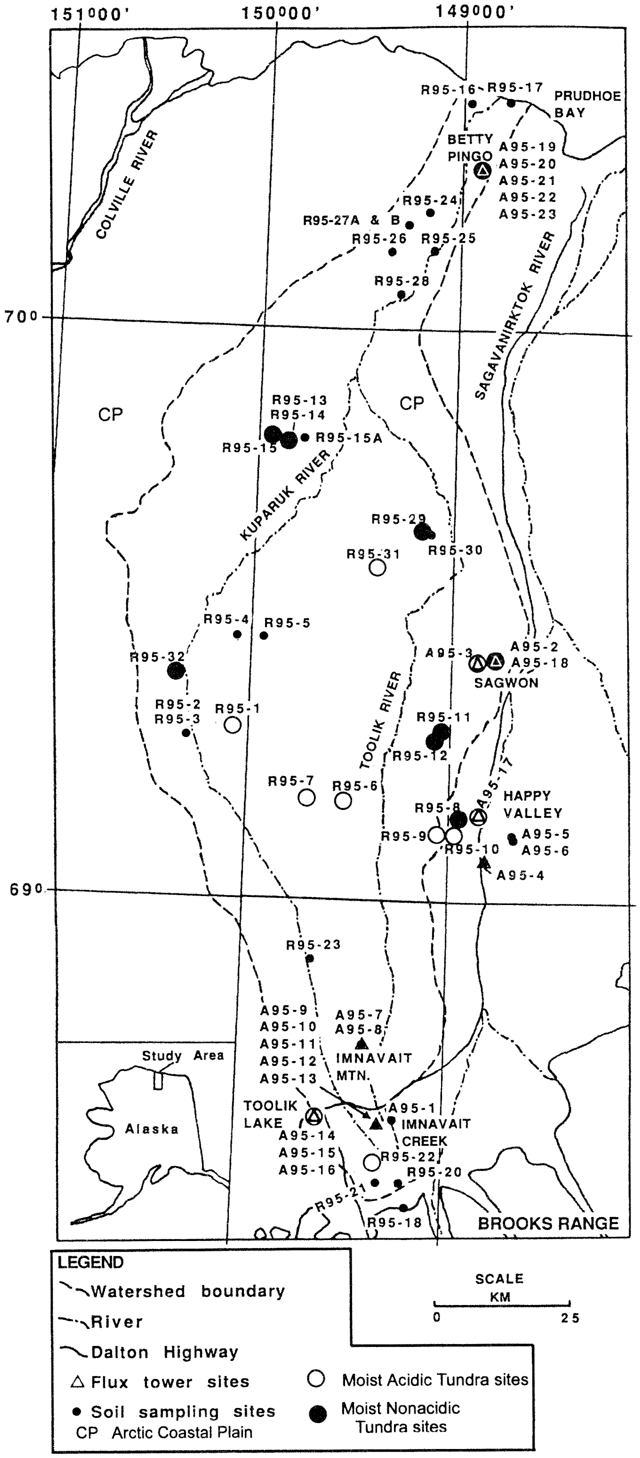

FIGURE 1. Location of sampling sites in the Kuparuk basin, northernmost Alaska, including moist nonacidic tundra (solid circles) and moist acidic tundra (open circles).

and other dwarf-shrub species, such as *Ledum palustre* L. spp. *decumbens* (Ait.) Hult., *Vaccinium vitis-idaea* L. ssp. *minus* (Lodd.) Hult., *V. ulignosum* L., *Salix planifolia* Pursh. spp. *pulchra* (Cham.) Argus, and *Sphagnum* moss (Walker et al., 1994).

All soils selected for analysis are derived from silty materials. Parent materials generally are either recent loess or older loess reworked by glaciation and/or mass wasting (arctic foothills) or thaw-lake cycles (arctic coastal plain) (Kreig and Reger, 1982; Carter, 1988).

SAMPLE COLLECTION

Two sets of samples were collected. Thirty-two pedons were sampled during a helicopter-supported reconnaissance to prepare landcover and soil maps of the watershed; these are designated as R95-1 through R95-32 on Figure 1. These pedons were in major landcover types selected from aerial photographs and using a global positioning system (GPS) unit. The pedons were excavated to the surface of the frost table in early August when the active layer was near its maximum thickness. The upper 10 to 20 cm of frozen ground was sampled using a hammer and cold chisel.

An additional set of detailed pedons, designated as A95-1 through A95-23 (Fig. 1), was examined at 11 tower sites for measuring CO_2 and methane fluxes along a roughly north-south gradient from Betty Pingo near Prudhoe Bay (70°17′N) to Imnavait Creek (68°30′N). These pits were dug by hand to the frost table and excavated farther to 100 cm with a gasoline-powered Pico impact drill. Only the silt-rich soils under moist nonacidic and moist acidic tundra were included in the present study.

Soil descriptions were made in accordance with procedures detailed by the Soil Survey Division Staff (1993). Bulk samples were collected from each horizon and placed in water-tight bags. Soils were classified according to the recently adopted Gelisol order in *Soil Taxonomy* (ICOMPAS, 1996).

Bulk density cores were taken from each horizon of the detailed pedons within the active layer. Bulk density of reconnaissance pedons and frozen horizons was estimated from the equation, $y = 1.374 * 10^{-0.026x}$, where y = bulk density (g cm^{-3}) and x = organic carbon (%). This equation was derived from 82 measurements from the detailed pedons and had an r^2 of 0.823 ($P = 0.0001$). The equation may overestimate the bulk density of frozen horizons containing abundant massive ice. Soil pH was measured on a saturated paste within 8 h of sample collection using a portable pH meter.

Tissue samples were collected from major plant species at Sagwon Bluffs, a locality containing both moist nonacidic tundra (sites A95-2 and A95-18) and moist acidic tundra (sites A95-3). For nonwoody plants such as the sedges, mosses, and forbs, the entire aboveground portion of the plant was harvested. For woody shrubs such as *Arctous rubra, Salix,* and *Betula,* the foliage and branches were sampled separately. Fourteen species (including combined forbs) were sampled in moist nonacidic tundra and 10 species in moist acidic tundra. *Carex bigelowii, Cassiope tetragona* (L.) D. Don ssp. *tetragona,* and *Hylocomium splendens* occurred in both landcover types.

During an accuracy assessment of the landcover map (Muller et al., in press), visual estimates were made of the percent cover of nonsorted circles at 63 moist nonacidic tundra sites and 80 moist acidic tundra sites in the Kuparuk River basin.

LABORATORY ANALYSES

Soil samples were shipped to the University of Wisconsin where bulk density (reported on samples dried at 105°C) and gravimetric and volumetric field moisture contents were determined. Air-dried samples were ground to pass a 2-mm screen. One set of subsamples was oven-dried at 105°C, ground to pass a 0.25-mm screen, and sent to the University of Alaska-Fairbanks Agriculture and Forestry Experiment Station at Palmer for total carbon and nitrogen analysis on a Leco CHN-1000 analyzer. No adjustments were made for $CaCO_3$ so that the carbon values represent organic and inorganic forms. A second set of subsamples was sent to the University of Missouri Soil Char-

TABLE 1

Morphological properties of soils in moist nonacidic and moist acidic tundra

Profile no.	Active layer depth (cm)	Organic thick. (cm)	A horizon thick. (cm)	B horizon thick. (cm)	Solum thick-ness (cm)	pH O hor.	pH B hor.	B hor. tex-tural class	Color A hor.	Color B hor.	Soil subgroup[a]	Parent materials
Moist nonacidic tundra and dry tundra												
A95-2	72	24	0	45	72	7.4	7.3	sil	(not present)	10YR 4/2	R.-H. Aquaturbel	Loess/outwash
A95-18	71	3	0	32	71	8.0	7.9	sil	(not present)	10YR 3/2	T. Aquaturbel	Loess/outwash
A95-19	43	0	21	0	42	7.3	7.4		2.5YR 2.5/1		T. Molliturbel	Loess and lacustrine
A95-21	49	17	41	>41	82	7.7	7.3	sil	5YR 2.5/1	7.5YR 3/2	T. Mollihaplel	Silty lacustrine
R95-4	83	1	17	16	62	7.0	6.9	sil	10YR 4/2	10YR 4/1	T. Aquaturbel	Silty colluvium
R95-8	30	23	10	0	40	6.6		sil	(not present)		T. Aquaturbel	Silty colluvium
R95-11	50	26	8	16	50	7.1	6.3	sicl	7.5YR 3/2	10YR 4/1	T. Histohaplel	Silty colluvium
R95-12	60	14	6	30	60	7.3	6.3	l	10YR 3/1	10YR 4/2	T. Aquaturbel	Colluvium
R95-13	64	8	43	13	64	7.1	7.4	l	5YR 2.5/1	7.5YR 3/2	T. Molliturbel	Loess
R95-15	46	7	9	16	32	7.7	6.8	sil	7.5YR 2.5/1	2.5Y 3/1	T. Aquaturbel	Loess/outwash
R95-29	52	9	32	27	52	7.1	7.1	sil	10YR 3/2	10YR 3/2	R.-H. Aquaturbel	Silty colluvium
R95-32	70	5	55	0	60	7.2	6.7	sil	10YR 3/1		T. Mollihaplel	Loess
Avg. (n = 12)	58	11	20	18	57	7.3	7.0					
SD	15	9.2	18	15	15	0.37	0.49					
SE	4.3	2.6	5.2	4.3	4.3	0.11	0.14					
Moist acidic tundra												
A95-3	45	16	0	24	42	4.0	5.5	sil	(not present)	10YR 4/1	T. Aquaturbel	Loess
A95-9	35	18	0	12	35	4.6	4.9	l	(not present)	7.5YR 4/4	T. Aquahaplel	Loamy till
A95-10	48	23	0	17	48	4.5	5.2	l	(not present)	10YR 4/1	T. Histoturbel	Silty colluvium
A95-15	44	11	0	24	50	4.5	5.2	l	(not present)	10YR 5/2	T. Aquaturbel	Loamy till
A95-17	39	10	0	18	40	4.4	5.2	sicl	(not present)	10YR 5/1	T. Aquaturbel	Loess/till
R95-1	34	32	0	0	32	4.1	5.3	sil	(not present)		T. Histohaplel	Silty colluvium
R95-6	41	9	0	6	41	4.3	5.4	sil	(not present)	2.5Y 4/1	T. Aquaturbel	Silty colluvium
R95-7	46	22	0	0	22		6.4	sicl	(not present)		T. Histohaplel	Silty colluvium
R95-22	61	11	0	28	39		5.2	sil	(not present)	2.5Y 5/2	T. Aquahaplel	Silty till
R95-31	47	4	0	32	36		5.0	sicl	(not present)	2.5Y 4/1	T. Aquahaplel	Colluvium
Avg. (n = 10)	44	16	0	16	39	4.3	5.3					
SD	7.7	8.3	0	11	8.0	0.22	0.41					
SE	2.5	2.5	0.0	3.5	2.5	0.07	0.13					
P[b]	0.019	0.281	0.002	0.553	0.0017	0.0000	0.0000					

[a] R = Ruptic, H = Histic, T = Typic.

[b] P = probability based on Analysis of Variance.

acterization Laboratory, where the following analyses were done using methods established by the Soil Survey Staff (1996): particle-size distribution (method 3A), NH_4OAc-extractable bases (5B1), $BaCl_2$-triethanolamine-extractable acidity (6H1), cation-exchange capacity (CEC) by NH_4OAc at pH 7.0 (5A1), CEC by sum of cations following extraction with NaOAc at pH 8.2 (5A3a), KCl-extractable Al (5B3), Bray P-1 absorbed P (6S3), base saturation by summation (5C3), and base saturation from NH_4OAc.

Nutrient contents of the profiles were determined to a depth of 100 cm by taking the product of nutrient concentration, bulk density, and horizon thickness. In a few cases we were unable to excavate the soils to 100 cm. In those cases we extrapolated the last horizon, which was usually a Cgf or a Cg/Oajjf, to 100 cm. The percentage of coarse fragments was low and no corrections were necessary for skeletal material.

Tissue samples were dried at 65°C, ground in a laboratory mill, digested in concentrated HNO_3 and $HClO_4$, and total elemental analysis was performed on an inductively coupled plasma emission spectrometer by the University of Wisconsin Soil and Plant Analysis Laboratory. Comparisons in soil properties and percent nonsorted circles between moist nonacidic and moist acidic tundra were done by one-way analysis of variance and two-sample t test, respectively.

Results

SOIL MORPHOLOGY AND CLASSIFICATION

Soils under moist nonacidic tundra contain an 11 ± 2.6-cm-thick organic layer over a dark-colored A horizon (average thickness = 20 ± 5.2 cm) and a gleyed Bg horizon. The A horizon occasionally qualifies as a mollic epipedon, a dark colored and relatively thick surface mineral horizon that is enriched in organic C and has a base saturation of 50% or more (Table 1). Soils under moist acidic tundra have a thicker organic horizon and lack an A horizon. The Bg horizon in soils of the moist acidic tundra often displays dilatancy, which is a property of saturated soils enriched in coarse silt whereby the volume and moisture content changes upon deformation (Alexander, 1992). Soils under moist nonacidic tundra have a significantly ($P \leq 0.05$) deeper seasonal thaw (active) layer (58 cm) than soils under moist acidic tundra (44 cm).

Aquaturbels, mineral soils that are cryoturbated and have

TABLE 2

Laboratory data for selected soils in moist nonacidic tundra and moist acidic tundra

										Extractable bases (cmol(+) kg^{-1})							Base
Horizon[a]	Depth (cm)	pH	C (%)	N (%)	C:N	Clay (%)	Silt (%)	Sand (%)	Extr. P (mg L^{-1})	Ca	Mg	Na	K	Ex. acid.	Ex. Al	CEC	sat. (%)
Moist Nonacidic Tundra																	
A95-18																	
Oi	0–3	7.96	40.7	1.15	35				4.4	117	11	0.1	1.1	20.9	0	129	100
B/A	3–35	7.91	4.00	0.25	16	18.5	69.2	12.3	0.0	22.7	1.6	TR	0.1	2.3	0	24.4	100
Bw	35–47	7.69	4.44	0.28	16	17.8	68.3	14.0	0.0	23.0	1.6	TR	0.1	1.6	0	24.7	100
C/Ajj	47–71	7.08	5.67	0.40	14	24.0	65.2	10.8	0.7	33.4	2.4	TR	0.2	5.1	0	36	100
Ajj/Cf	71–85	7.18	8.26	0.49	17	15.0	71.5	13.4	2.4	35.4	2.7	TR	0.1	5.1	0	38.3	100
R95-4																	
A	0.5–18	7.57	3.95	0.27	15	15.4	76.3	8.2	0.2	21.0	3.8	TR	0.2	1.4	0	25.1	100
Bg	18–34	7.50	3.01	0.18	17	17.2	77.1	5.7	0.3	16.6	2.4	TR	0.2	2.3	0	19.2	100
BC	34–62	7.69	2.81	0.19	15	18.7	77.7	3.6	0.5	16.7	3.1	TR	0.2	2.3	0	20	100
A/Cjj	62–72	7.65	4.95	0.35	14	25.1	72.3	2.5	0.4	30.0	3.1	TR	0.2	4.4	0	33.4	100
Ajj	72–83	7.49	9.66	0.62	16	22.4	74.6	3.0	0.4	50.5	3.5	0.1	0.2	7.9	0	54.3	100
R95-13																	
Oi	0–2	7.75	34.6	1.86	19												
Oa	2–8	7.32	26.0	1.67	17				1.2	112	5.8	0.1	0.3	17.2	0	118	75
A/Bjj	8–32	7.88	7.12	0.48	15	15.8	29.9	54.4	0.0	37.6	1.9	TR	0.1	4.4	0	39.6	100
B/Ajj	32–45	7.67	5.93	0.41	14	19.8	35.0	45.2	0.0	34.6	1.2	TR	0.1	3.4	0	35.9	100
Oajj	45–64	7.20	15.3	1.01	15	22.1	46.2	31.7	0.8	77.0	2.6	0.1	0.1	12.7	0	79.8	100
Moist Acidic Tundra																	
A95-3																	
Oi	0–6	5.04	47	1.13	42				38.4	32.7	6.1	0.3	2.8	74.4	1	80.1	52
Oe	6–16	5.29	42.2	2.06	20				12.4	63.1	5.7	0.3	0.6	68.4	0.3	97	72
Bg	16–40	5.92	4	0.30	13	26.8	65.3	7.9	0.7	16.4	1.6	TR	0.1	17.8	0.2	28.5	64
Oejj	40–42	5.81	20.0	1.27	16				1.5	32.7	1.9	TR	0.1	52.4	0.4	76	46
Oajj/Cgf	42–65	6.41	23.2	1.28	18	23.8	57.0	19.1	0.1	62.8	4.4	0.1	0.2	46	0	96.7	70
Cg/Oajjf	65–87	7.12	9.61	0.45	21	16.2	77.0	6.8	0.1	33.4	2.3	TR	0.2	5	0	36	100
A95-17																	
Oi	0–9	4.36	46.6	1.14	41				39.2	18	5	0.1	0.2	75.7	1.2	97	27
Oe	0–30	5.71	38	1.68	23				21.2	12.8	2	0.1	0.5	70.8	4	83.2	19
Oijjf	0–61	5.61	33.0	1.40	24				9.6	9.3	1.1	TR	0.2	67.3	4	71.6	15
Bgjj	0–40	5.17	1.84	0.09	20	23.5	66.8	9.7	0.2	2.7	1.6	TR	0.1	14.6	4	14.6	30
Cgjj	0–50	5.00	1.5	0.08	19	21.8	67.8	10.4	1.0	1.7	0.8	TR	0.1	13.4	4.2	14.1	18
R95-1																	
Oi	0–8	4.11	46.8	1.14	41				47.6	31	8.7	0.2	2.9	82.1	0.8	100	42
Oe	8–24	4.25	49.4	1.18	42				42.0	22.7	5.6	0.1	2.3	69.7	0.3	93.9	33
Oa	24–36	5.94	39.8	1.67	24				9.2	55.4	6.8	0.1	0.4	59.3	0.1	108	58
Cg	36–37	5.85	5.64	0.31	18	16.3	78.3	5.4	0.1	11.3	1.9	0.1	0.1	18.3	0.6	26.5	51
Cgf	37–50	5.67	8.2	0.48	17	16.4	74.5	9.1	0.0	13.2	1.9	0.1	0.1	25.4	0.6	33.4	46

[a] New soil horizon nomenclature for permafrost-affected soils (Gelisols) includes "jj" for horizons showing cryoturbation (ICOMPAS, 1996).

aquic conditions, are dominant in each landcover type (Table 1). Whereas 75% of the pedons investigated in the moist nonacidic tundra are cryoturbated (i.e., classified as Turbels), only 50% are cryoturbated in the moist acidic tundra. Four of the 12 pedons examined in the moist nonacidic tundra have mollic epipedons and are classified as Mollihaplels, mineral soils with minimal cryoturbation and a mollic epipedon, or Molliturbels.

PARTICLE SIZE DISTRIBUTION

For comparative purposes the soils were chosen for their similarity in parent material composition. All except five of the pedons are in coarse-silty or fine-silty texture classes and have silt-loam textures within the 25 to 100 cm depth interval (Table 1). The silt concentration for all soils averages 55% (Table 2). There are no significant differences in the profile quantities of silt or clay between soils of the two landcover classes (Table 3).

CHEMICAL SOIL PROPERTIES

The pH values of the uppermost organic horizon and B horizon are 7.3 and 7.0 for the moist nonacidic tundra and 4.3 and 5.3 for the moist acidic tundra (Table 1). There are similar quantities of clay and total C in the upper 100 cm of the two broad soil groups (Table 3). Nevertheless, there are significantly greater amounts of extractable Ca, Mg, and sum of bases and significantly lower amounts of exchangeable acidity and Al in profiles of moist nonacidic tundra than in profiles of moist acidic tundra. These trends are due partly to the existence of free carbonates in soils of moist nonacidic tundra. For this reason, the

TABLE 3

Profile (0–100 cm) quantities of weathering products and nutrients in moist nonacidic and moist acidic tundra in the Kuparuk basin

Profile	Tot. C (kg m^{-2})	Tot. N	Clay	Silt	Extr. P (g m^{-2})	Ex. Ca (mol(+) m^{-2})	Ex. Mg	Ex. Na	Ex. K	Ex. bases	Ex acid.	Ex. Al	Ex. cations	CEC NH_4OAc	CEC sum
Moist nonacidic tundra															
A95-2	54.1	3.72	200	624	0.98	425	24.7	0.145	1.85	451	36.3	0	488	293	451
A95-18	61.2	3.89	213	764	0.8	621	23.1	0.113	1.43	645	40.3	0	686	344	645
A95-19	36.6	2.4	19	57	1.01	108	5.4	0.218	0.18	113	35.4	0	149	135	114
A95-21	97.8	6.13	92	273	0.05	393	13.3	1.388	0.61	408	51.9	0.1	459	311	408
R95-4	48.8	3.48	190	757	0.37	500	31.6	0.273	1.99	534	34.1	0	568	287	534
R95-8	64.3	3.87	129	341	0.15	89	6	0.571	1.34	98	210	5.9	308	269	104
R95-11	52.2	3.46	272	377	0.53	221	57.4	2.645	2.66	284	216	1.4	500	415	285
R95-12	51.3	3.52	167	328	1.45	253	84	5.498	8.9	352	99.6	0	451	409	352
R95-13	76.2	6.04	136	270	0.3	511	15.7	0.401	0.74	528	61.1	0	589	430	528
R95-15	72.2	5.51	110	334	0.07	406	32	0.08	0.31	438	85.4	0	524	450	438
R95-29	47.6	3.67	267	626	1.81	298	39	0.105	2.14	339	84	0.1	423	388	339
R95-32	52.6	3.72	217	657	0.58	440	35.9	0.092	1.84	478	35.1	0.3	513	319	478
Avg.	59.6	4.12	168	451	0.68	355	30.7	0.96	2.00	389	82	0.7	472	338	390
SD	16.3	1.15	74	226	0.56	164	22.4	1.62	2.31	164	65	1.7	138	89	163
SE	4.7	0.33	21	65	0.16	47	6.5	0.47	0.67	47	19	0.5	40	26	47
Moist acidic tundra															
A95-3	53.6	2.92	107	325	0.55	210	12.3	0.177	0.944	223	103	0.6	326	226	224
A95-9	47.2	2.32	141	331	3.84	19.6	4.6	0.233	1.02	25.4	159	19.8	184	148	45.1
A95-10	44.1	1.89	173	355	1.14	7.5	4.3	0.153	0.291	12.9	164	34.9	176	156	47.8
A95-15	36.5	1.76	183	339	1.74	9.8	4.5	0.02	0.531	16.6	143	25.7	158	128	40.9
A95-17	34.1	1.6	239	727	1.52	26	11.5	0.124	1.205	39.1	181	46.5	220	190	85.3
R95-1	58.7	3.04	88	402	0.92	84	12.5	0.579	1.045	98.2	158	3.3	257	213	102
R95-6	66.6	3.46	144	355	1.02	130	32.6	0.667	2.78	166.4	197	14	364	297	182
Avg.	48.7	2.43	154	405	1.53	70	11.8	0.28	1.12	83	158	20.7	241	194	104
SD	11.8	0.72	50	144	1.09	77	10.0	0.24	0.80	83	30	16.6	79	58	72
SE	4.4	0.27	19	55	0.4118	29	3.8	0.09	0.30	31	11	6.3	30	22	27
P[a]	0.14	0.005	0.66	0.64	0.035*	0.0005**	0.051*	0.288	0.35	0.0003**	0.011*	0.0005**	0.0008**	0.001**	0.0004**

[a] *P* = probability based on Analysis of Variance.

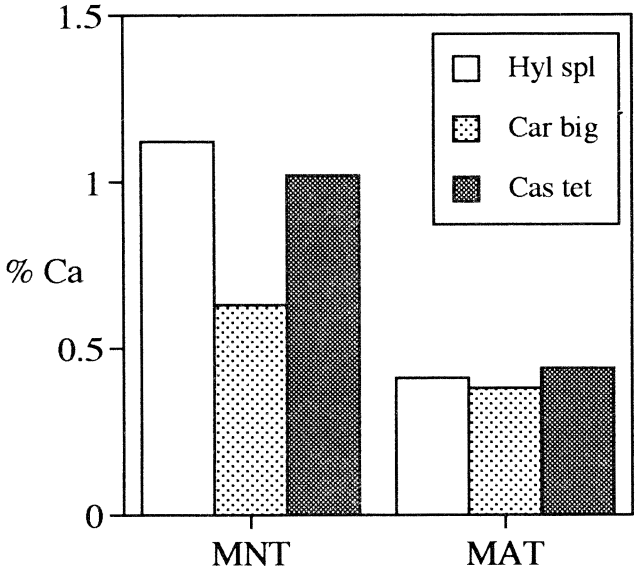

FIGURE 2. A comparison of tissue concentrations of Ca for plant species in moist nonacidic tundra (MNT) and moist acidic tundra (MAT), including Hylocomium splendens *(Hyl spl),* Carex bigelowii *(Car big), and* Cassiope tetragona *(Cas tet).*

cation-exchange capacities as determined by extraction with 1M NH_4OAc and by sum of cations are greater in soils of moist nonacidic tundra than in soils of moist acidic tundra. Whereas profile N is significantly greater in moist nonacidic tundra, profile extractable P is significantly greater in moist acidic tundra (Table 3).

PLANT TISSUE CONCENTRATIONS

Concentrations of Ca are two to three times greater for plant species on moist nonacidic tundra than for equivalent species on moist acidic tundra (Fig. 2; Table 4). Manganese concentrations are nine-fold greater in plant tissues of moist acidic tundra than for tissues in moist nonacidic tundra.

Discussion

Soils of nonacidic tundra have thinner organic horizons, a deeper thaw depth, greater quantities of extractable Ca, Mg, and sum of bases, and lower quantities of extractable acidity and Al than soils of moist acidic tundra on parent materials of similar composition (Fig. 3; Tables 1, 3). A greater proportion (75%) of soils in the moist nonacidic tundra are cryoturbated than in the moist acidic tundra (50%) (Table 1). In addition, visual estimates during the helicopter-supported reconnaissance show a significantly greater area occupied by nonsorted circles in moist nonacidic tundra (9.6%, n = 63) than in moist acidic tundra (0.9%, n = 80) (Fig. 3).

These trends suggest that nonacid conditions, thin organic layers, deep thaw, and cryoturbation are mutually reinforcing. Cryoturbation mixes organic matter and mineral soil throughout the active layer and exposes the mineral soil. Numerous field observations on the Alaskan North Slope indicate that the potential for cryoturbation is enhanced at upland sites with moist conditions and relatively deep thaw (Walker and Walker, 1996). Site-specific conditions necessary to produce mass displacement include a reversed vertical density gradient and loss of intergranular contacts between soil particles (Vandenbergh, 1988). Development of differential freezing rates as a consequence of local variations in snow cover, vegetation density, and soil moisture can lead to cryostatic pressures within a refreezing active layer (Nicholson, 1976). Mackay (1980) showed that patchy vegetation cover promotes local increases in thaw depth, forming bowl-shaped depressions in the base of the active layer that ultimately give rise to mass displacements within the soil. Indeed, mudboils are common within the Kuparuk basin, but are less common in surrounding undisturbed and continuously vegetated areas that often support moist acidic tundra.

Williams and Smith (1989) suggested that many of the soil structures attributed to cryoturbation are the result of differential frost heaving that is related to localized high soil moisture content. Most work on cryoturbation has focused on soil processes and properties at specific locations or within small areas. Broad inferences about permafrost and the active layer, and their relation to climatic change, have been made on the basis of soil cryoturbation features, usually at widely spaced locations (Maarleveld, 1981). Despite an early recommendation by Benninghoff (1952), there has been no systematic, regional-scale effort to examine the spatial distribution of cryoturbation features and their relation to other environmental variables such as winter surface soil temperature, distribution of snowcover, and the thickness of the organic mat.

Although there is a relationship between the occurrence of moist nonacidic tundra and widespread cryoturbation, the general trend in the region over a millennial scale is toward acidic tundra. During the process of paludification, the soils, even on moderate slopes, become waterlogged, and the accumulation of organic matter and mosses, chiefly *Sphagnum,* contribute to the acidification of the soils (Walker et al., 1989; Walker and Walker, 1996).

Therefore, in areas of moist nonacidic tundra, some external factor maintains the nonacidic conditions. This factor could be modern loess deposition that contributes Ca and other base cations to the system. However, this process occurs primarily in highly braided reaches of streams in the coastal plain and in proximity to major rivers in the arctic foothills (Carter, 1988; Walker and Everett, 1991). The soils for this study were selected so as to be distributed throughout the Kuparuk River basin and not chiefly in the coastal plain or adjacent to the Sagavanirktok River (Fig. 1).

These data imply that some landscape factor is either enhancing cryoturbation in nonacidic areas or influencing vegetation production/decomposition in nonacidic areas that in some way results in thin organic horizons. The conversion of moist nonacidic tundra to moist acidic tundra may be explained as follows. Cryoturbation inhibits the development of a *Sphagnum* mat and mixes base cations, mainly Ca and Mg, originating within the system or contributed externally as wet and dry deposition. Changes in environmental conditions which to date have not been explained allow a *Sphagnum* mat to develop. The *Sphagnum* releases protons that replace base cations on soil exchange sites (Sjörs, 1950; Gorham, 1956; Clymo, 1963); the base cations are subsequently lost to subsurface flow (Everett et al., 1989).

Regardless of the causes of nonacidity in any given place (it could vary from place to place), it results in the set of linked soil and vegetation properties described here. The differences in base cations in moist nonacidic and moist acidic tundra soils have important implications regarding ecosystem functioning. For example, moist nonacidic tundra vegetation apparently cycles larger amounts of base cations, especially Ca, than moist acidic tundra vegetation. This is reflected by the high tissue concentrations of Ca and Mg in moist nonacidic tundra (Fig. 3).

TABLE 4

Tissue chemistry of Moist Nonacidic Tundra and Moist Acidic Tundra at Sagwon Bluffs, Alaska

Species	Tissue	N	P	K	Ca	Mg	S	Zn	B	Mn	Fe	Cu	Al
		(%)						(mg kg^{-1})					
		Moist Nonacidic Tundra											
Arctus rubra	leaves	1.2	0.1	0.39	1.32	0.13	0.06	43.4	12.8	45	120	3.7	112
Arctus rubra	branches	0.6	0.06	0.16	1.06	0.14	0.06	811.5	10.3	37	133	4	83
Carex bigelowii	aboveground	0.7	0.07	0.3	0.63	0.06	0.06	31.6	4.2	318	259	8.1	243
Cassiope tetragona	aboveground	0.6	0.06	0.2	1.02	0.08	0.06	15.3	9.2	176	265	4.5	254
Cetraria cucullata	aboveground	0.3	0.05	0.2	1.67	0.05	0.02	16	3	66	261	2.6	249
Dryas integrifolia	aboveground	0.7	0.07	0.18	2.57	0.13	0.05	33.5	11.1	109	388	4.2	342
Eriophorum triste	aboveground	1	0.12	0.54	0.64	0.09	0.08	33.3	8.6	303	195	5.6	156
Forbs	aboveground	1.5	0.11	0.45	1.58	0.25	0.07	13.7	19.8	80	168	8	130
Hylocomium splendens	aboveground	0.6	0.06	0.21	1.12	0.11	0.05	16.1	9.5	152	462	3.9	361
Lupinus arcticus	aboveground	1.1	0.08	0.66	5.47	0.44	0.05	21.5	14.9	152	96	3.1	179
Rhododendron lapponicum	aboveground	0.7	0.07	0.23	0.38	0.05	0.06	68.2	10.2	102	119	7.9	126
Rhytidium rugosum	aboveground	0.7	0.08	0.26	1.23	0.15	0.06	17.8	14.6	237	725	3.1	567
Salix glauca	leaves	1.5	0.11	0.58	1.59	0.36	0.13	106.6	14.3	71	81	2.6	58
Salix glauca	branches	0.5	0.06	0.33	1.17	0.07	0.04	133.9	11.5	91	58	2.7	53
Salix lanata	leaves	1.6	0.14	0.66	3.14	0.41	0.12	153.3	21.8	51	54	2.6	39
Salix lanata	branches	0.6	0.06	0.22	0.88	0.07	0.04	98.8	12.1	25	39	3.4	42
Salix reticulata	leaves	1.1	0.1	0.57	2.46	0.25	0.08	104.3	20.2	100	146	3.9	165
Salix reticulata	branches	0.5	0.08	0.27	1.27	0.11	0.04	127.2	11.9	97	151	3.8	132
Tomentypnum nitens	aboveground	0.5	0.05	0.2	1.65	0.14	0.04	19	11.3	264	642	4.3	594
	Average	0.8	0.08	0.35	1.62	0.16	0.06	98.2	12.2	130	230	4.3	204
		Moist Acidic Tundra											
Betula nana	leaves	0.6	0.09	0.22	0.6	0.3	0.04	367.4	26.5	3714	118	5	142
Betula nana	branches	0.7	0.09	0.24	0.2	0.07	0.05	357.7	10.1	593	65	4.2	70
Carex bigelowii	aboveground	1	0.06	0.8	0.38	0.09	0.11	31.4	5.8	685	139	4.2	70
Cassiope tetragona	aboveground	0.9	0.08	0.19	0.44	0.07	0.05	31.3	6.9	742	126	3.7	135
Eriophorum vaginatum	aboveground	0.9	0.09	0.36	0.21	0.07	0.07	39.7	5.6	575	124	4.5	83
Hylocomium splendens	aboveground	0.6	0.07	0.24	0.41	0.07	0.05	102	4.4	823	206	3.5	187
Ledum decumbens	leaves	1.3	0.14	0.44	0.49	0.12	0.08	22.2	17.9	2042	56	4.3	106
Ledum decumbens	branches	0.6	0.08	0.19	0.27	0.06	0.05	29.9	9.1	1336	72	5.1	87
Salix pulchra	leaves	1.1	0.06	0.19	0.84	0.2	0.08	246.6	11.8	1441	55	3.2	69
Salix pulchra	branches	0.7	0.08	0.24	0.75	0.08	0.06	367.2	13.6	560	47	3.1	54
Sphagnum lenense	aboveground	0.4	0.04	0.26	0.42	0.09	0.03	39.1	3.1	402	161	2.7	163
Sphagnum warnsdorfii	aboveground	0.6	0.07	0.34	0.38	0.09	0.04	76.6	4.1	643	152	12	161
Vaccinium vitis-idaea	aboveground	0.7	0.08	0.27	0.64	0.13	0.05	34.4	11.7	3068	59	4.6	194
	Average	0.8	0.08	0.31	0.46	0.11	0.06	134.3	10	1279	106	4.6	117

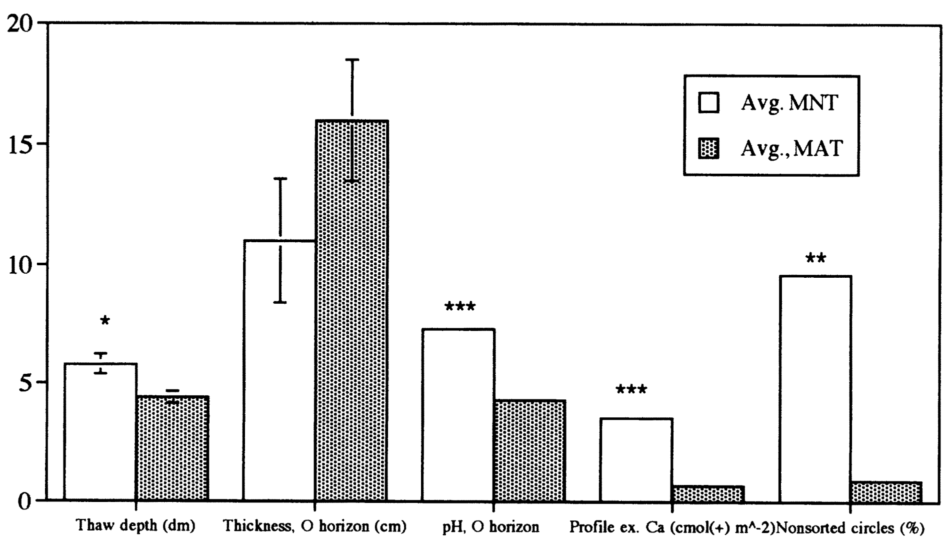

*FIGURE 3. A comparison of key properties between moist nonacidic tundra and moist acidic tundra. Statistical comparisons are made using Analysis of Variance (errors show ± 1 standard deviation; * = significant at P = 0.05 and *** = significant at P = 0.0001).*

Lupinus arcticus has unusually high amounts of base cations, including a Ca concentration in excess of 5% (Table 4). Micronutrients such as Mn and Zn are less available at high pH values in moist nonacidic tundra as evidenced by lower tissue concentrations of these elements than in moist acidic tundra.

Moist nonacidic tundra has a greater plant diversity than moist acidic tundra (Walker et al., 1994) and possibly a greater variety of habitats for wildlife use. The greater abundance of Ca in plants of moist nonacidic tundra may be important for lactation and horn and bone production of ungulates (Bryant and Kuropat, 1980). Plants of the nutrient-poor moist acidic tundra tend to have an abundance of protective chemical compounds that limit their palatability as forage.

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