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ABSTRACT

The physical and chemical properties of Arctic tundra soils were studied along a 250-km latitudinal transect in northern Alaska. The transect includes the nonacidic tundra of the Arctic Coastal Plain, the moist nonacidic tundra of the northern Arctic Foothills, and moist acidic tundra of the southern Arctic Foothills. The parent material of the coastal plain consists of carbonate-rich alluvium. The northern foothills have a mantle of calcareous loess. Further south the parent materials are moraines of late Quaternary. Vegetation changes from sedges on the coastal plain, to grasses on the northern foothills, and tussock and shrub tundra in southern foothills. Following the same order, soil pH and base saturation decrease and soil acidity increases. Most of the soil exchangeable acidity and cation exchange capacity are from soil organic matter.

Keywords: Alaska, Gelisols, soil acidity, tundra soils

INTRODUCTION

Arctic Alaska is underlain by continuous permafrost. It consists of two physiographic provinces: the Arctic Coastal Plain and the Arctic Foothills. The Arctic Coastal Plain has a mean annual air temperature (MAAT) of -12^{o}C, and mean annual precipitation (MAP) of 130 mm with 50% as snow. The mean annual soil temperature (MAST) at 50 cm ranges from -7^{o} to -9^{o}C (Osterkamp and Romanovsky, 1996). The parent material is carbonate-rich alluvium of Holocene age. The dominant vegetation includes sedges and mosses (Walker et al., 1998). The Arctic Foothills are located between the Arctic Coastal Plain and the northern foot slopes of the Brooks Range. There are two main types of landcover in the region; moist nonacidic tundra (MNT) and moist acidic tundra (MAT). The MNT is dominated by a mixture of dwarf shrub-sedge and the MAT by a mixture of cottongrass-shrub and mosses (Walker et al., 1998). Parent materials include carbonate-rich loess of Holocene age in the northern foothills and moraines of early to late Pleistocene in the south (Hamilton, 2003). The MAAT of the Arctic Foothills is -9^{o}C. The MAST ranges from -5^{o} to -7^{o}C, and the MAP ranges from 140 to 270 mm with 40% falling as snow. The MAAT, MAP and winter temperatures increase southward with distance from the coast.

Arctic tundra soils have unique properties that result from cryoturbation due to frost heave. Cryoturbation causes mixing of soil material by repeated freezing and thawing, results in broken and irregular horizons, for example, organic material may be mixed into mineral soil, particularly near the permafrost table (Bockheim and Tarnocai, 1998; Ping et al., 1998). Cold temperatures and wetness retard organic matter decomposition, thus facilitating the accumulation of peat in arctic regions. Most of the soils in arctic Alaska are classified Gelisols, an order for permafrost-affected soils in Soil Taxonomy (Soil Survey Staff, 1999). These soils may become potential carbon sources with climate warming and thawing of the carbon-rich near-surface permafrost.

Most previous soils studies were focused soil geography but less on soil chemistry and their cryogenic nature (Everett and Brown 1982). Based on a study in a localized area at the northern foothills, Valentine and Binkley (1992) concluded that the topography is primarily responsible for sol pH variations among all controlling factors. Walker et al. (1998) realized the pH boundary between the MNT and MAT and its implications in ecology and wildlife habitat. Ping et al. (1998) found that key to the nature of this boundary is that soil pH and base saturation changes along a climate transect from the Arctic Coast to the Brooks Range. The purpose of this paper is to examine the nature and development of soil acidity in the context of Jenny’s (1941) five soil-forming factors.

MATERIALS AND METHODS

Soil Sampling and Soil Analyses

Study-site locations are listed in Table 1. All sites were chosen as representative of the major land cover classes in Arctic Alaska. Soil profiles were described and sampled according to the Soil Survey Manual (Soil Survey Division Staff, 1993). Soil horizons in the upper permafrost and those cryoturbated are designated by lowercase *f and jj*, respectively. All soil samples were weighed, air-dried, reweighed, and then crushed to pass through a 2-mm sieve. Analytical results are on an oven-dry basis. All samples were characterized according to the USDA National Soil Survey Laboratory procedures. Soil analysis included pH (1:1), total OC, cation exchange capacity (CEC) and extractable cations, base saturation (pH 7), exchangeable acidity ($BaCl_2$-TEA), and particle size analysis (pipet method).

RESULTS AND DISCUSSION

Soil pH and Base Saturation

There is a general trend of increased base saturation with increased pH values (R^2=0.76, $p<0.01$, Fig. 1). The variation in this relationship can largely be attributed to the variety of soils across the latitudinal transect with differing parent materials, age, degree of weathering and leaching conditions. The data can be divided into two groups using the Cate-Nelson (1971) analysis (Fig. 1) with soils having a pH of <6.5 and a BS <70%, and those with pH

>6.5 and a BS of >70%. This pH value is generally observed for soils transitional from MNT to MAT (site 5&6).

Arctic Coastal Plain: Nonacidic tundra range pH ranges from 6.0 to 8.5. Higher values are found in wet nonacidic tundra (Sites 1-3) and pH decreases to south where elevation increases (Site 4 and 5). There is a general trend of increased pH with depth except where there is a cryoturbated organic horizon. High pH and BS values indicate that the soils are carbonate-saturated and calcium carbonate buffered. The Cf horizon in the upper permafrost usually has the highest pH. It is the layer where any Ca leached downward would accumulate and also where bases may precipitate out of solution as water freezes due to freezing-front concentration of salts by salt-exclusion (Hallet, 1978). However, is no pH depth function in Sites 3 to 5 as they are highly cryoturbated soils with surface organic horizons mixed with underlying mineral horizons. All these soils have 100% BS and Ca^{++} remains the predominant exchange cation (Ping et al., 1998) throughout.

Arctic Foothills: On the northern fringe of the foothills, soils formed in Holocene loess (Walker and Everett, 1991) and soil pH changes from pH 7.7 in site 5 to pH 5.6 in Site 6 as BS drops from 100% to 34-70%. Site 5 and 6 represent two soils across the MNT and MAT boundary. Both the pH values and base saturation indicate the nonacidic-acidic transition.

On the southern foothills soils formed on moraines of different ages. Soils of Site 8 formed on the most recent moraine (ca. 9000 YBP, Brown and Kreig, 1982) and the pH values ranges from 6.5 to 7.0. However, as the ages of the landscape increases from late-Pleistocene (Sites 9 and 10) to middle Pleistocene (Sites 7, 11, and 12), the pH values dropped to an average of 4.8 and BS dropped from 80 to 10%. In soils of the temperate regions, both pH and B.S. commonly show a distinct increase with depth due to cation leaching. Relative to soils without frost boils, soils with frost boils have strong cryoturbation that mixes acid-organics with soil carbonates resulting in an increased reaction of acids and carbonates in the profile and increased soil acidification. With landscape age there is an increased time for acid production and for the mixing acidification-reaction to occur.

Cation Exchange Capacity, Organic Carbon and Exchangeable Acidity

Arctic Coastal Plain: The CEC (pH 7) of the organic horizons range from 31 to 245 cmol(+) kg^{-1} with mineral horizons ranging from 3 to 32 cmol(+) kg^{-1}. In both MNT and MAT soil CEC is significantly correlated to %OC (r=0.94, p<0.01 and r=0.82, p<0.01, respectively, Fig. 2). The strong relationship of CEC and %OC is largely due to the magnitude difference in CEC and %OC between organic and mineral soils (high and low, respectively). With more limited range of %OC in mineral soils the variability in the relationship of CEC and %OC increases with a lower correlation (r=0.58, p<0.1). Inclusion of clay content of mineral soils decreased variability with some increase in the correlation(r=0.69, p<0.01) indicating that as %OC decreases the role of clay content becomes more important. Soil CEC increased more dramatically by OC content in MNT compared to MAT (slope for the relationship were: m=5.5 and 2.0 for MNT and MAT respectively). There is poor correlation for all mineral soils, between CEC and clay content (r=0.58, ns) due to weak weathering and clay minerals dominated by kaolinite and mica with a minor fraction as vermiculite and smectite (Borden et al., 2004). Calcium is the dominant exchange cation (>90% of the CEC, data not shown). Exchangeable cations were concentrated in the surface organic horizons indicating biocycling effects. High pH and BS in the arctic coastal plain reflect the influence of the parent materials and landform. Runoff is slow and permafrost causes negligible leaching in lowlands that restricts the removal of carbonates.

Arctic Foothills: Soils of both Site 5 and 6 are both silt loams with similar clay contents. For these two close-proximity sites, the correlation coefficient (r) for CEC and %OC in mineral soils is 0.79 (p<0.06), but for CEC and % clay is 0.33 (ns). The distribution of CEC, exchange acidity and cations again lacks a clear depth relationship as observed in soils of temperate regions. Thus there is also very little net downward leaching of soluble salts. The MAT has more OC cryoturbated into the lower horizons than the MNT sites to the north.

Multiple regression analysis indicates that OC is the major contributor of exchange sites and acidity (Fig. 1) for the southern foothills. In most horizons, the exchange acidity at pH 8.2 is equal or exceeding the CEC pH 7, indicating that the pH-dependent charge on OC contributed nearly all the exchange sites with again Ca^{++} dominating exchange sites (Ping et al., 1998). The abundance of exchange cations correlates well with OC content ($r=0.83$, $p<0.01$) indicating cations are largely held by OC exchange sites.

On the foothills, the vegetation community changes along the pH gradient (Walker et al., 1998). Vegetation of MNT is dominated by grass and herbs with MAT dominated by ericaceous shrub, tussock sedges and mosses (Sphagnum moss). On the older moraines shrubs dominant (Site 11 and 12) and organic horizon thickness increases along with soil acidity. Sphagnum moss is a strong acidifier protonating the underlying mineral soils. The exchangeable Al increases under the acidic environment and the mineral horizons range from 1.0-4.5 cmol(+) kg^{-1} with the highest in the mid- to late-Pleistocene moraines (Ping et al., 1998).

FACTORS CONTROLLING SOIL ACIDITY

The acidification process in the arctic tundra soils of northern Alaska can be explained by Jenny’s five soil forming state factors: parent material, topography, climate, vegetation and time (Jenny, 1941). Parent materials include carbonate rich glacial drift and loess in the foothills and alluvium in the arctic coastal plain. On the Arctic Coastal Plain the nearly level relief and the presence of shallow permafrost results favor the accumulation of carbonates that buffer against acidification. Drainage improves on uplands (foothills) permitting the removal of free carbonates and acidification. This process is illustrated by the increased acidity decreased Ca^{++} moving up the foothills to the south.

The gradients in elevation and increased precipitation and temperature (climate changes) from north to south also favor the leaching of carbonates and thus enhance soil acidification (Ping et al., 1998). Vegetation also plays a role in acidification. Acidification is enhanced by protonation from species as Sphagnum moss. Age is a denominator of soil processes. Free carbonate content is in reverse relationship to the age of the parent materials with an opposite relationship for soil acidity and exchangeable Al. In conclusion, this study indicated that soil organic matter is the primary source of acidity in the Arctic tundra of Alaska.

ACKNOWLEDGEMENT

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Table 1. Locations of study sites, soil classification and selected soil properties.

Horizon	Depth	pH	Ex. H^+	CEC	BS	OC	Clay	Sand
	cm		cmol(+) kg^{-1}			%		
Site 1: Sapristel, 70.28° N. -148.90° W.								
Oa1	0 - 12	7.1	17	107	84	23.2	11	42
Oa2	12 -15	6.6	13	31	57	15.4	7	51
Oa3	15 -33	6.6	18	66	73	21.7	10	30
Ofjj	33 - 49	7.3	12	135	91	25.4	1	89
Cf/Wf	49 - 100	8.1	ND[1]	ND	100	0.3	ND	ND
Site 2: Aquorthel, 70.28° N. -148.8° W.								
Oi	0 - 4	7.7	ND	ND	100	19.4	ND	ND
Oa	4 - 13	7.1	ND	ND	100	18.2	ND	ND
Bg	13 - 34	6.8	4	25	83	4.5	16	51
Oab	34-69	6.0	21	67	68	19.0	ND	ND
Cf	69-100	8.5	ND	ND	100	0.4	12	78
Site 3: Aquiturbel, 70.16° N. –148.5° W.								
Oe/Oa	0 – 3		ND	ND	ND	ND	ND	ND
Bwjj1	3 – 15	7.9	ND	12	100	5.9	20	29
Bwjj2	15 - 40	8.0	ND	12	100	5.6	22	29
Bgjj1	0 – 35	8.0	ND	9	100	5.3	22	29
Bgjj2	40 – 68	8.1	ND	12	100	5.6	20	29
Cf1	68 – 92	8.0	ND	5	100	6.7	8	52
Cf2	92 – 100	8.1	ND	3	100	6.1	8	66
Site 4: Molliturbel, 69.68° N. –148.69° W.								
Oe	0 – 7	7.2	14	91	100	18.7	10	52
Ajj	7 – 35	7.5	ND	12	100	5.5	19	37
Bwjj	20 – 44	7.5	ND	7	100	3.2	18	36
Abjj	60 – 70	8.0	ND	28	100	9.7	20	37
Bg1jj	29 – 70	7.6	ND	13	100	4.9	20	36
Bg2jj	50 – 62	7.7	ND	15	100	6.6	19	37
Bg3jj	44 – 62	7.7	ND	9	100	3.6	19	34
Oabjj	62 – 80	7.9	ND	45	100	14.2	ND	ND
Cf1	80 – 90	7.5	ND	4	100	3.1	6	66
Cf2	90 - 100	7.5	ND	3	100	3.1	4	67
Site 5: Molliturbel, 69.43° N. -148.66° W.								
Oijj	0 - 10		21	245	70	38.5	ND	ND
Oejj	10 – 28	6.7	28	139	100	27.4	ND	ND
Oifjj	28 – 40	ND	ND	ND	ND	ND	ND	ND
Bwjj	0 – 30	7.5	5	27	100	2.8	26	10
Bgjj	30 – 50	7.7	5	32	100	2.8	25	10
Bgjjf	50 - 65	7.7	6	31	100	3.2	25	8
Bg/Oaf/Cf	65 - 100	7.9	6	40	100	10.2	25	9
Site 6: Aquiturbel, 69.42 ° N.-148.79° W.								
Oijj	0 – 8	4.3	87	87	41	48.9	ND	ND
Oejj	8 – 16	5.9	60	142	100	43.4	ND	ND
Bgjj	16 - 22	5.6	15	21	60	4.1	27	4
Oajj/Bgf	22 - 40	5.6	15	55	58	14.0	27	4
Oa/Bgjjf	40 - 52	5.3	27	44	34	11.3	29	5
Bg/Oajjf	52 - 75	5.9	19	33	70	13.5	26	5

Table 1. Continued

Horizon	Depth	pH	Ex. H^+	CEC	BS	OC	Clay	Sand
	cm		cmol(+) kg^{-1}				%	
Site 7: Aquiturbel, 69.15° N. -148.85° W.								
Oijj	0 – 7	7.9	61	85	75	36.7	ND	ND
Oejj	15 – 25	4.9	59	69	65	41.4	ND	ND
Bgjj1	4 – 20	5.1	19	17	41	3.2	29	12
Bgjj2	0 – 20	5.1	20	17	32	3.0	28	12
Oajj	40 – 52	5.0	28	24	48	7.2		
Bgjj3	20 – 40	5.0	20	17	31	4.2	27	13
Bgjj4	7 – 35	4.8	20	17	37	3.6	27	13
Oejj	40 – 52	4.7	81	66	37	23.0	ND	ND
Oejj/Cf	52 – 62	4.8	52	42	42	15.9	ND	ND
Bgjj5	25 – 35	4.7	16	17	45	3.8	26	13
Cf	62 -100	5.2	38	44	62	9.4	27	9
Site 8: Aquiturbel, 68.63° N. -149° W.								
Oa	0-30	6.8	31	203	85	44.5	4	26
Bgjj1	30-39	7.0	4	19	78	2.2	12	54
Bgjj2	39-65	6.9	4	19	78	2.0	15	50
Cf	65-100	6.5	8	25	69	3.6	19	44
Site 9: Aquiturbel, 68.63° N. -149° W.								
Oi	0 - 7	6.1	53	92	42	47.9	ND	ND
Oa	7 – 17	5.9	51	70	27	25.6	ND	ND
Ajj	17 - 20	5.3	41	50	18	12.9	38	24
Bgjj	20 - 33	5.0	15	19	19	2.7	24	36
Cf	33 - 80	5.1	13	15	15	2.7	26	33
Site 10: Aquiturbel, 68.63° N. –149.62° W.								
Oi	0 - 8	4.8	66	74	29	45.0	ND	ND
Oejj	8 – 20	6.1	28	57	31	28.1	23	38
Oajj	20 - 22	5.6	29	28	16	20.9	27	34
Bwjj	22 - 33	5.0	17	13	10	4.2	28	34
Bgjj	33 - 45	4.8	20	16	59	4.3	28	35
Cf	45 -100	4.9	19	15	55	6.1	ND	ND
Site 11: Aquiturbel, 68.61° N. -149.31° W.								
Oi	0-12	5.3	85	137	38	53.6	ND	ND
Oajj	12-17	5.5	91	118	23	31	ND	ND
Bgjj	17-24	5.0	23	26	11	5.3	22	34
BCjj	24-40	4.9	22	24	8	4.0	21	36
Cf	40-100	5.2	15	18	12	2.9	20	37
Site 12: Aquiturbel, 68.61° N. -149.30° W.								
Oi	0 - 7	4.8	71	39	53	48.0	ND	ND
Oe	7 - 16	4.9	58	78	15	39.8	ND	ND
Bgjj	16 - 25	4.8	24	17	10	5.4	31	38
Cf1jj	25 - 40	4.9	21	18	11	7.5	30	41
Cf2	40 - 80	4.9	23	20	15	8.9	30	40

[1]ND indicates not determined.

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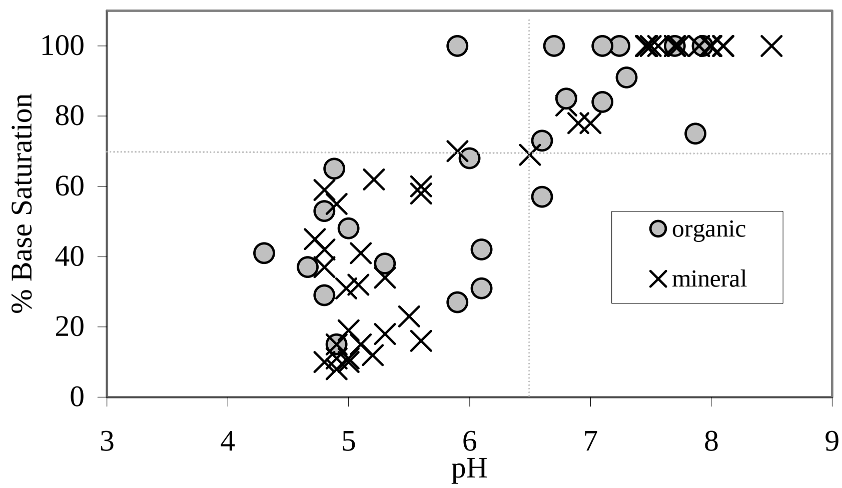

Figure 1. Relationship between base saturation (BS %) and pH in arctic tundra soils, northern Alaska.

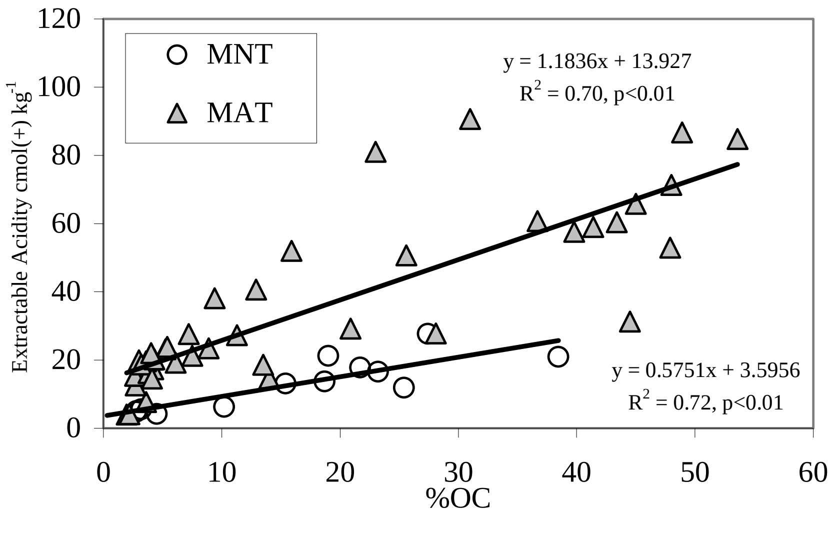

Figure 2. Relationship between exchange acidity and %OC in arctic tundra soils, northern Alaska.