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Soil Nutrients and Vegetation Characteristics of a Dorset/Thule Site in the Canadian Arctic

ALISON M. DERRY,[1] PETER G. KEVAN[1,2] and SUSAN D.M. ROWLEY[3]

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ABSTRACT. We conducted a systematic study of soils and vegetation present at Arnaqquaksaat on Igloolik Island, Nunavut, a site occupied by Dorset and Thule people prior to 1823 and probably for over a thousand years. We compared this site to an area affected by ongoing mammal and bird activity and an area of relatively unfertilized polar semidesert. At these locations, we estimated percent cover of vegetation, identified vascular plant species, measured soil depth, and collected soil samples. The soil samples were analyzed for total nitrogen, sodium bicarbonate-extractable phosphorus, available potassium, available magnesium, and pH.

Percent plant cover, abundance of plant species indicative of enrichment, and soil depth were greatest within the area of anthropogenic influence and decreased downslope to the sea. Total nitrogen level in the upslope area of anthropogenic influence (2.61% ± 0.88) was similar to that in areas of bird and mammal activity (2.54% ± 0.78); it was higher than the levels in the downslope area of human fertilization (0.65% ± 0.82) and the unaltered polar semidesert area (0.28% ± 0.38). Phosphorus levels in the influenced areas were 5 to 6 times those in the uninfluenced polar semidesert. The magnesium level was highest in the area of bird and mammal activity (766.8 mg/L ± 53.35), whereas potassium levels were similar throughout the study area. The lowest pH was found in the upslope area of past human occupation, and pH differences among sites paralleled those observed for nitrogen.

Key words: anthropogenic disturbance, archaeological site, Arctic, Igloolik, nutrients, soil, vegetation

RÉSUMÉ. On a effectué une étude systématique des sols et de la végétation présents à Arnaqquaksaat dans l'île Igloolik au Nunavut, un site occupé par les peuples de Dorset et de Thulé avant 1823 et probablement durant plus de mille ans. On a comparé ce site à une zone affectée par l'activité continue de mammifères et d'oiseaux et à une zone de semi-désert polaire relativement non fertilisé. À ces endroits, on a évalué le pourcentage de couvert végétal, identifié les espèces de plantes vasculaires, mesuré la profondeur du sol et prélevé des échantillons de sol. On a analysé ces derniers pour en évaluer la teneur en azote total, phosphore extractible par le bicarbonate de soude, potassium disponible, magnésium disponible et le pH.

On a trouvé que le pourcentage de couvert végétal, l'abondance d'espèces végétales révélatrice d'un enrichissement et la profondeur du sol étaient les plus importants à l'intérieur de la zone qui avait subi une influence anthropique et qu'ils décroissaient en descendant vers la mer. Le niveau d'azote total dans la zone supérieure de la pente, qui avait subi une influence anthropique (2,61 p. cent ± 0,88), était semblable à celui des zones où s'exerçait l'activité des oiseaux et des mammifères (2,54 p. cent ± 0,78); il était supérieur aux niveaux trouvés dans la partie inférieure qui avait connu une fertilisation humaine (0,65 p. cent ± 0,82) et dans la zone polaire semi-désertique non altérée (0,28 ± 0,38). Les niveaux de phosphore dans les zones ayant subi une influence étaient de 5 à 6 fois ceux des zones semi-désertiques polaires n'ayant pas subi d'influence. Le niveau de magnésium était le plus haut dans la zone où s'exerçait l'activité des oiseaux et des mammifères (766,8 mg/L ± 53,35), alors que les niveaux de potassium étaient semblables dans toute la zone d'étude. Le pH le plus bas se trouvait dans la zone supérieure de l'endroit ayant jadis été occupé par l'être humain, et les différences dans le pH parmi les sites s'alignaient sur celles observées pour l'azote.

Mots clés: perturbation anthropique, Arctique, sol, végétation

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INTRODUCTION

In the Arctic, human habitation and animal activity have profound effects, which may endure for hundreds of years (Lutz, 1951; Porsild, 1955; McCartney, 1979). The arctic environment severely limits plant growth because of the cool, short growing season, low levels of nutrients, and—in polar desert and semidesert areas—little water (Svoboda, 1977; McCown, 1978; Woodley and Svoboda, 1994). Nitrogen is the primary limiting nutrient in most arctic soils, followed by phosphorus (Haag, 1974; Svoboda, 1977; Chapin, 1987; Muc et al., 1994). In the Arctic, nutrients entering biogeochemical cycles are less available to plant growth than in more southerly areas largely

[1] Department of Environmental Biology, University of Guelph, Guelph, Ontario N1G 2W1, Canada
[2] Corresponding author: pkevan@uoguelph.ca
[3] 6660 Forest Glen Rd., Pittsburgh, Pennsylvania 15217, U.S.A.

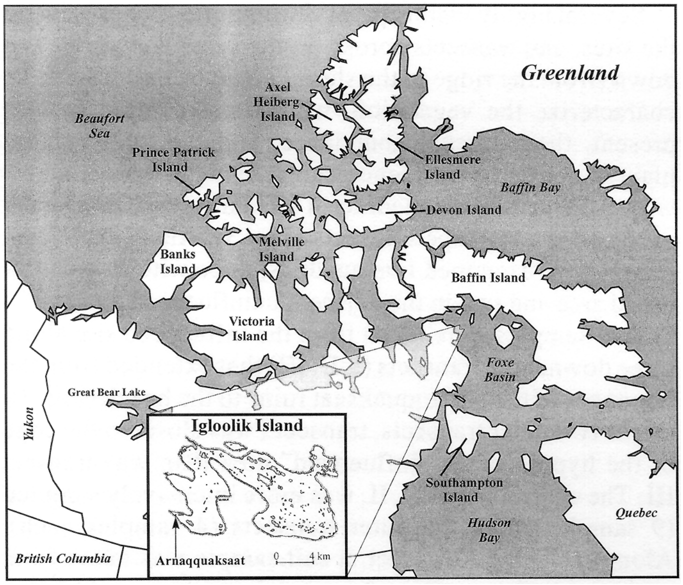

FIG. 1. Map showing the location of the area of enrichment from past human habitation and associated activities at Arnaqquaksaat on Igloolik Island, Nunavut, Canada.

because low temperatures hinder organic matter decomposition and microbial nitrification (Haag, 1974; Svoboda, 1977; McKendrick et al., 1980). Although cold soils do not limit the uptake of nitrogen by plants, they do reduce the uptake of phosphorus (Haag, 1974). Some human and animal activities alter biogeochemical cycles by adding nitrogen and phosphorus into the ecosystem (Rastetter et al., 1991). Higher levels of soil nutrients result in higher growth rates of arctic plants, which then enhance rates of nutrient cycling (Hobbie, 1995).

Where there is adequate moisture, human and animal activity can alter the biogeochemical cycling of arctic ecosystems both directly and indirectly, because nitrogen and phosphorus inputs increase growth of mosses and other plants (Lutz, 1951; McCartney, 1979; Rastetter et al., 1991; Forbes, 1994). Nutrient-enriched areas have greater soil depth, greater vegetation cover (Bliss and Gold, 1994), and characteristic plant species that differentiate them from the surrounding landscape. Increased plant growth in turn promotes cycling of nutrients. Even a small amount of organic production and decomposition results in a large increase in nutrient availability (Shaver et al., 1992). Cyanobacteria associated with mosses fix biologically significant amounts of nitrogen (Karagatzides et al., 1985), and mosses often dominate the vegetation in wetter areas. This dominance results in an accumulation of peat, which decomposes slowly because of the presence of cellulose and antibiotic compounds and the somewhat anaerobic conditions of waterlogging (Russel, 1990). Microorganisms in these enriched sites have greater functional diversity than those in adjacent unenriched sites (Derry et al., 1998).

Our aim was to compare the soil characteristics and vegetation in an anthropogenically enriched area, areas enriched by mammal and bird activity, and adjacent areas of unaltered polar semidesert. All the sites are on Igloolik Island, Nunavut, Canada, on raised beach dominated by cushion plants, and represent a polar semidesert type of vegetation (Svoboda, 1977). The site of anthropogenic fertilization was within an area identified with ruins from both Dorset and Thule cultures, where much organic deposition once occurred from walrus and whale processing and refuse associated with human habitation (Rowley, 1997). The occupation on this site, dated from over 1000 years ago to about 150 years ago (Rowley, unpubl. data), resulted in large-scale organic deposition. Parry and Lyon noted that the houses were unoccupied in 1823, but that does not indicate that they had been abandoned (Rowley, 1997). Large amounts of organic matter and plant species indicative of nitrogen and phosphorus enrichment are often associated with Dorset/Thule sites today (McCartney, 1979; Forbes, 1996). The site we chose offers an excellent opportunity to study how soils and vegetation in polar semidesert have been altered by Dorset/Thule occupation.

MATERIALS AND METHODS

Study Sites

The study site, called Arnaqquaksaat, is located on the southwestern tip of Igloolik Island, Nunavut (69° 22′ N, 81° 47′ W; See Fig. 1). The area, characterized as mid to high Arctic, has less than 200 mm of annual precipitation (mostly snow). It has cold temperatures in winter (-30˚C to -35˚C February means, as measured in a standard meteorological screen) and cool summers (5˚C to 10˚C July means) about 15 weeks long (McKay et al., 1970). Arnaqquaksaat (Borden Number NiHf-4) is along the slope of a raised limestone beach (Dredge, 1991) where there are ruins of Thule and Dorset stone, sod, and whalebone houses (11 m above sea level) that predate 1823. On top of a ridge 50 m high are ten Thule houses and at least four Dorset semisubterranean dwellings. Just below the ridge is a Thule tent ring, and farther downslope are another four Thule house ruins and some caches (Rowley, 1997). Lemming burrows were evident around the rocks. Although the highest parts of the study site emerged from the sea 1000 years ago through isostatic rebound (Dredge, 1992), lower areas emerged as recently as 700 years ago (Rowley, 1997). The site of presumed anthropogenic fertilization is approximately 8600 m^2 of almost continuous plant cover that begins in front of the main line of dwellings and extends downslope to the sea (Fig. 2). We divided the study site into "influenced" and "uninfluenced" areas: the "influenced" area showed obvious difference (almost continuous plant cover) from the surrounding "uninfluenced" polar semidesert at the same elevation, which appeared relatively pristine and had much less vegetation. We subdivided the influenced part of the site into an "upper area" (7 to 69 m downslope from the house entrances) and a "lower area" (69 to 110 m downslope from the house

FIG. 2. Aerial photograph of Arnaqquaksaat on Igloolik Island, Nunavut, showing the area of anthropogenic influence (at centre) and the surrounding, uninfluenced tundra. Foxe Basin is visible at bottom right and in the strip of water beyond Arnaqquaksaat at upper left, while the water seen at bottom left is a lagoon. The area of anthropogenic influence extends downslope from left to right. Its dark bottom margin is a strip of *Saxifraga tricuspidata.* The line running through the upper margin of the same area is a vehicle track.

entrances) for comparisons of soil depth, total percent plant cover, and soil chemistry (Fig. 3).

In the surroundings (less than 500 m from the site fertilized by past human activity), surface soils from around bird perches on large, isolated rocks (i.e., not part of rock complexes that might have been anthropogenic) were used to examine the effects of mammals and birds on soil nutrient content. Rocks used as bird perches were easily identifiable by the presence of regurgitated bird pellets, feces, a bright orange lichen, *Xanthoria elegans* (Thomson, 1979), and many lemming burrows. The rocks chosen, at approximately the same elevation as Arnaqquaksaat, were assumed to be about the same geological age as the site of anthropogenic fertilization. Unenriched polar semidesert (within 50 m of the human-influenced study area and within about 200 m of the bird perch rocks) was the area hypothesized to be "uninfluenced" by humans.

Field Methods

Rastetter et al. (1991) reported that most of nitrogen present within an arctic ecosystem is found in the soil (including the permafrost) rather than in the vegetation. Because nitrogen is a limiting nutrient to plants on the tundra (Haag, 1974), soil nitrogen content was used to indicate patterns of nutrient enrichment. Low levels of soil phosphorous can restrict nitrogen fixation, so we measured phosphorous in the soil as well. Data collection occurred over four days from 25 to 28 August 1996.

Soil depths (which included peat, where present) were measured, using a metal probe and tape measure, at about 0.9 m intervals along six cross-slope transects (perpendicular to the slope) that were 15 to 30 m apart across the site. The transects crossed the entire influenced area and extended 9.5 to 14.5 m into the uninfluenced area on either side (Fig. 3).

Several highly visible plant communities are present on the sites, and transects across (at the same elevation) and down (from the ridge to the shore) could be delineated. To characterize the vegetation, we estimated plant species present, their percent abundance, and the total percent plant cover on the influenced area, using cover estimates within 0.5 m × 0.5 m quadrats at 14 m intervals along each of the six cross-slope transects (Fig. 3). Along each 70 m transect, we examined five quadrats, three within the influenced area and two in the adjacent uninfluenced areas.

Soil samples were taken from the influenced site along three downslope transects (I, II, III) that extended from the entrances of the Arnaqquaksaat ruins to the beach (Fig. 3). Of the two outer transects, transect I was closer to the edge of the hypothesized "influenced" area than was transect III. The central transect, II, was more intensively sampled (9 samples) than the outer transects (4 samples each). Along the central transect, a soil sample was taken from each vegetation zone and each transition area between zones: (1) house entrance zone; (2) transition area; (3) thick vegetation and moss zone; (4) transition area; (5) thin vegetation and moss upper plateau zone; (6) outwash area; (7) thin vegetation and moss lower plateau zone; (8) beach fringe; and (9) beach (Fig. 3). Along the two side transects, soil samples were taken from a smaller array of vegetation zones: house entrance zone (a, w); thick vegetation and moss zone (b, x); thin vegetation and moss zone (c, y); and beach fringe (d, z; See Fig. 3). The soil cores were collected within the top 25 cm of soil, using a metal cylinder 9 cm long and 6.5 cm in diameter. The cores of soil, of 9 cm maximum depth, were packaged in labelled, zip-lock bags and frozen for transport to the analytical laboratory at the University of Guelph.

Similar methods of soil collection and preservation were used for samples from the area enriched by mammal and bird activities and the uninfluenced, adjacent areas of polar semidesert. Five bird perch boulders were chosen for sampling in a location within 500 m and at about the same elevation as the Dorset/Thule houses. Soil was sampled at the foot of each boulder, where the quantities of regurgitated pellets, feces, and lemming burrows were highest. Seven soil samples were also taken from polar semidesert areas near (< 200 m) the ruins that were presumed to be uninfluenced. The soils collected for nutrient analysis ranged from pure mineral soils (taken from areas without vegetation) to well-developed organic soils. Recognizable peat was removed from the organic soils and was not included in the soil cores.

Laboratory Methods

The soil samples remained frozen until ready for analysis at the Analytical Services Laboratory at Land Resource Sciences, University of Guelph. Analysis was a standard fertility package that included determination of total percent nitrogen, conducted on a Leco FP-428 Combustion System with a thermal conductivity detector; sodium

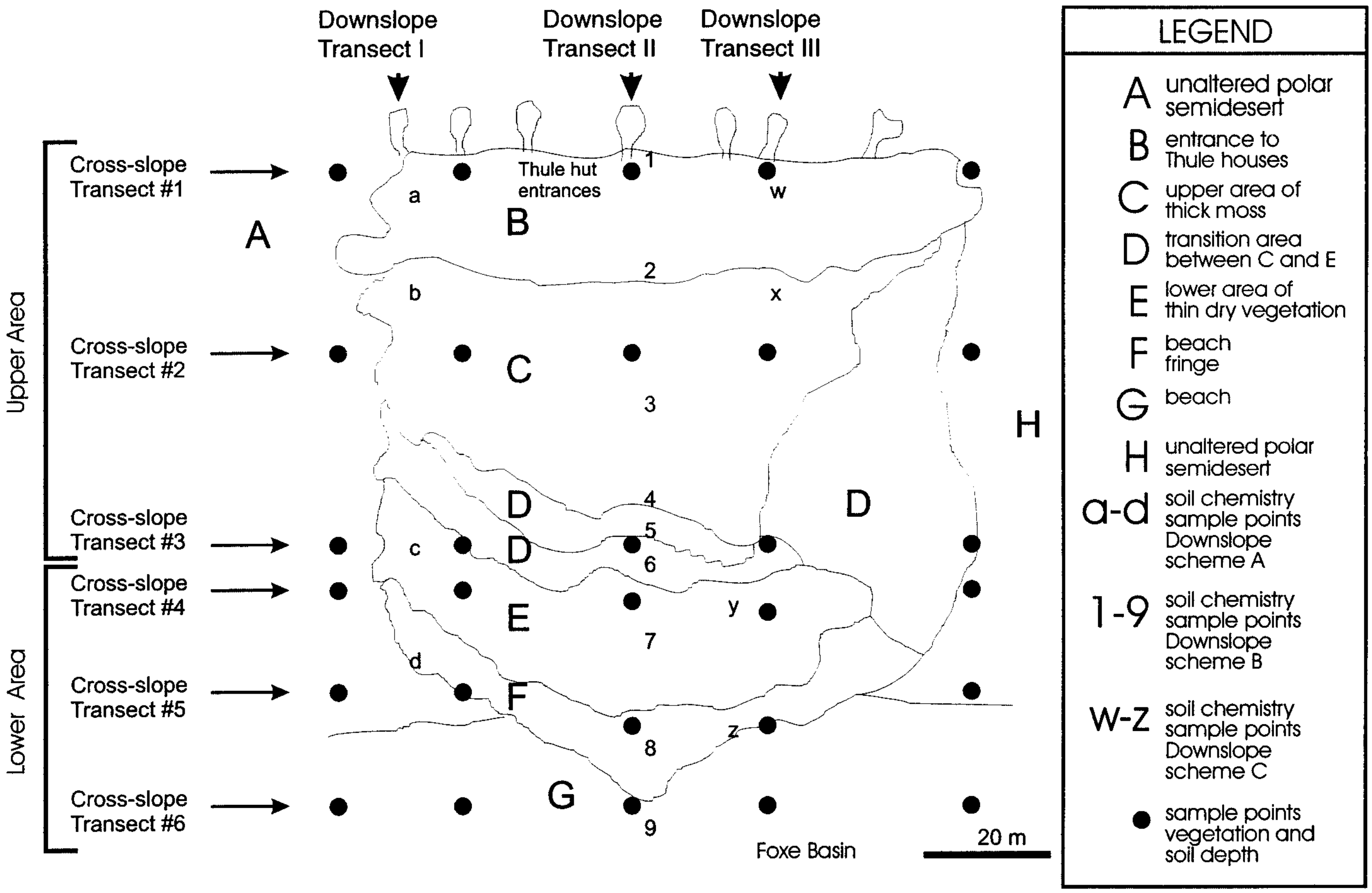

FIG. 3. Diagram of the area of anthropogenic influence at Arnaqquaksaat, Nunavut, showing vegetation zones (A–H), sampling points for soil chemistry (points a–d, 1–9, and w–z on downslope transects), and sampling points for soil depth and vegetation (black dots on cross-slope transects). The points outside the area of influence are semischematically presented for location between 9.5 and 14.5 m beyond the area of influence.

bicarbonate-extractable phosphorus (mg/L), using a Technicon Auto Analyzer according to ammonium molybdate blue methodology; available potassium and magnesium (mg/L), measured by atomic absorption spectrophotometry; and pH. These laboratory methods followed the outlines of the Ontario Soil Management Committee (Carter, 1993).

Statistical Analysis

Sigmastat software (Sigmaplot, Jandel Scientific, San Rafael, California 94912-7005, U.S.A.) was used to conduct statistical analyses. Soil depth, total percent plant cover, and soil chemistry were compared among sites, using either a one-way ANOVA, followed by a Student-Newman-Keuls test, or a Kruskal-Wallis one-way ANOVA on ranks, followed by a Dunn's multiple comparison test (Glantz, 1992). We used a Spearman rank correlation to test the null hypothesis, that total percent plant cover and soil nutrient levels were not related to distance downslope from the ruined houses, by calculating the probability that such a relationship would be different from zero. This nonparametric analysis was used to avoid the assumption that a linear relationship existed between the variables.

RESULTS

Soil Depth

Soil depth along the cross-slope transects (Fig. 3) ranged from about 2.5 cm up to 14 cm (Fig. 4). The greatest soil depths were near the centre of the area of anthropogenic enrichment. The shallowest soils (0 cm on loose broken stones) were generally less than 2.5 cm deep and occurred outside the area of presumed human influence (Table 1). Soil depth was significantly greater on the upper influenced area (11.59 ± 4.19 cm) than on the adjacent upper uninfluenced area (6.23 ± 3.27 cm) and the influenced area further downslope from the houses (2.54 ± 2.42 cm) (p <0.05, Dunn's test). The soil depth on the lower influenced area was significantly greater than on the adjacent lower uninfluenced area (1.84 ± 2.20 cm, p <0.05, Dunn's test; Table 1).

Vegetation

The vegetation zones, sampled along the cross-slope transects, were dominated by different plant species (Table 2). In Zone B (entrance to houses), *Salix arctica* was

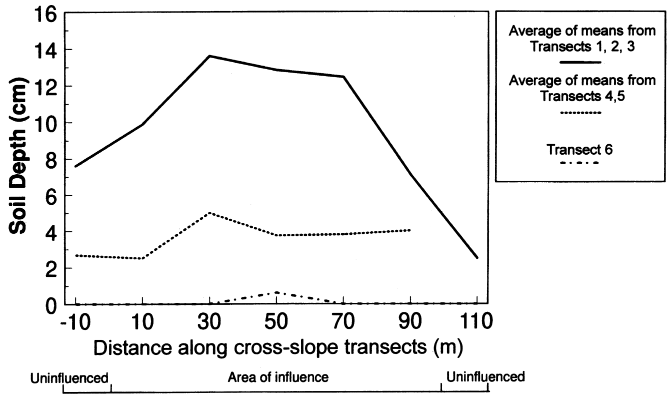

FIG. 4. Distance along cross-slope transects (m) versus soil depth (cm) on the area of anthropogenic influence at Arnaqquaksaat, Nunavut.

the dominant plant. Zone C (upper area of thick, moist moss and other vegetation) was dominated largely by the tall, loose turf moss, *Plagiomnium medium*. Zone D (a transition area between the wetter, more deeply vegetated upper area and the lower area of dry vegetation) was dominated by *Bryum* sp. and *S. arctica.* The dominant plants of Zone E (the lower area of thin, dry vegetation) were an assemblage of *Plagiomnium medium*, *Dryas integrifolia,* and *Bryum* sp. The beach fringe (Zone F) mainly had mixtures of *Saxifraga tricuspidata, P. medium,* and *Bryum* sp. The beach (Zone G) had very sparse vegetation, represented by *Bryum* sp. and a little *Saxifraga oppositifolia*. *Dryas integrifolia* dominated Zones A and H, which represented uninfluenced polar semidesert. Total percent plant cover on the upper influenced area was significantly greater (85.2 ± 19.6%) than on the adjacent upper uninfluenced area (38.1 ± 35.5%, $p < 0.05$, Dunn's test; Table 1).

Soil Chemistry

Total percent nitrogen was highest in the area enriched by ongoing mammal and bird activities (2.54 ± 0.78%) and the upper area of past enrichment from human habitation and activities (2.02 ± 1.18%; Table 1). Nitrogen concentrations at these sites were significantly higher than in the lower influenced area further downslope from the houses (0.44 ± 0.77%) and in the unaltered polar semidesert (0.28 ± 0.38%, $p < 0.05$, Student-Newman-Keuls test; Table 1). The level of sodium bicarbonate-extractable phosphorus was higher in the upper area of past human influence (11.00 ± 8.92 mg/L) and in the soils around the rocks that were subject to ongoing fertilization from birds and mammals (8.00 ± 5.79 mg/L) than in the lower area of anthropogenic influence (2.60 ± 0.89 mg/L) and the "uninfluenced" area on the polar semidesert (1.57 ± 0.98 mg/L, $p < 0.05$, Dunn's test; Table 1). There were no significant differences between sites in the amounts of available potassium. Available magnesium, however, was most concentrated in the soils around the bird rock perches, and its level there (766.80 ± 53.35 mg/L) was significantly greater than in the upper (450.60 ± 177.40 mg/L) and lower (143.80 ± 94.60 mg/L) areas of past human influence and the unaltered polar semidesert (237.10 ± 134.80 mg/L; $p < 0.05$, Student-Newman-Keuls test; Table 1). Values for soil pH were relatively neutral at all sites. Significant differences observed between the sites for soil pH, as revealed by the Student-Newman-Keuls test ($p < 0.05$), were the same as those demonstrated for total percent nitrogen (Table 1).

Spearman Rank Correlations

In the area of past human influence, the Spearman rank correlation coefficient (r_s) for total percent plant cover and distance downslope from the house entrances was -0.63, indicating a direct and significant relationship (Table 3). On the adjacent uninfluenced area, downslope from the same elevation as the house entrances and parallel to the downslope sampling schemes (transects I, II, and III) on the influenced area, there was a more significant decline in the total percent plant cover ($r_s = -0.83$; Table 3, Fig. 3). For total percent soil nitrogen and distance downslope, a significant relationship was found on the influenced area ($r_s = -0.83$), but not on the uninfluenced area ($r_s = -0.14$; Table 3, Fig. 5). We found significant correlations between magnesium levels and distance both within ($r_s = 0.83$) and outside ($r_s = 0.60$) the influenced area. Of interest is the correspondence of pH and distance downslope on the influenced area ($r_s = 0.70$), which was less pronounced on the adjacent, uninfluenced polar semidesert ($r_s = 0.56$; Table 3).

DISCUSSION AND CONCLUSIONS

Our study demonstrates the impact on soil development, vegetation growth, and soil chemistry of long-term fertilization from indirect and direct influences of human habitation and animal activity. The upslope area of past anthropogenic enrichment had significantly deeper soils than the adjacent "uninfluenced" area. Other authors have also noted greater soil development at archaeological sites compared to surrounding areas in the Arctic (Lutz, 1951; McCartney, 1979; Moore, 1986; Moore and Denton, 1988; Forbes, 1996). Higher concentrations of nitrogen (Lutz, 1951; McCartney, 1979; Forbes, 1996) and phosphorus (Lutz, 1951; Proudfoot, 1976; McCartney, 1979; Moore, 1986; Moore and Denton, 1988; Forbes, 1996) were correlated with these deeper soils.

Plant species characteristic of nitrogen- and phosphorus-enriched Arctic sites (McCartney, 1979; Forbes, 1996; Lewis and Belyea, n.d.) were present at the site of past anthropogenic fertilization. Although not dominant within the designated vegetation zones, vascular plants indicative of nutrient enrichment were found, including *Cerastium alpinum*, *Draba* sp., *Papaver radicatum*, *Polygonum viviparum*, *Saxifraga caespitosa*, *Saxifraga cernua*,

TABLE 1. Soil depth, percent total plant cover, total nitrogen, sodium bicarbonate-extractable phosphorus, available potassium, available magnesium, and pH (mean ± SD) on the area of human influence (Arnaqquaksaat), the area of bird and mammal influence (bird perches), and unaltered polar semidesert at Igloolik Island, Nunavut (69°22' N, 81°47' W).

	Polar semidesert area (raised beach terrain)		Area enriched by ongoing mammal and bird activities (bird rock perches)		Area enriched by past human habitation and activities (Upper Area)		Area enriched by past human habitation and activities (Lower Area)		Test Used: F = one-way ANOVA H = Kruskal-Wallis	
Soil depth Upper area (cm)	6.23	(3.27) a[1]	–	–	11.59	(4.19) b	2.54	(2.42) c	H = 92.0;	p <0.002
Soil depth Lower area (cm)	1.84	(2.20) a	–	–	–	–	2.54	(2.42) a	H = 1.33;	p = 0.249
Total Plant Cover (%)	38.10	(35.50) a	–	–	85.20	(19.60) b	49.50	(42.30) a, b	H = 8.48;	p = 0.014
Total nitrogen (% by dry mass)	0.28	(0.38) a	2.54	(0.78) b	2.02	(1.18) b	0.44	(0.77) a	F = 10.2;	p = 0.0001
Sodium bicarbonate-extractable phosphorus (mg/L)	1.57	(0.98) a	8.00	(5.79) a, b	11.00	(8.92) b	2.60	(0.89) a, b	H = 14.3;	p = 0.0025
Available potassium (mg/L)	54.60	(25.00) a	74.20	(45.36) a	66.60	(41.10) a	32.70	(10.40) a	H = 4.92;	p = 0.178
Available magnesium (mg/L)	237.10	(134.80) a	766.80	(53.35) b	450.60	(177.40) c	143.80	(94.60) a	F = 22.2;	p < 0.001
pH	7.54	(0.13) a	7.04	(0.11) b	7.01	(0.25) b	7.53	(0.335) a	F = 11.9;	p < 0.001

[1] Within each row, means accompanied by different letters (a, b, or c) are significantly different from one another ($p < 0.05$), as determined by one-way ANOVA followed by the Student-Newman-Keuls test, or by Kruskal-Wallis one-way ANOVA on ranks followed by Dunn's multiple comparisons test.

Saxifraga hieracifolia, *Saxifraga hirculus*, *Alopecurus alpinus*, *Arctagrostis latifolia*, *Poa hartzii* and *Dupontia* sp. The moss species found in this enriched area, *Plagiomnium medium* (dominant in Zone C) and *Bryum* sp. (dominant in Zones D and E) are particularly important because of their association with nitrogen-fixing cyanobacteria (including *Nostoc* sp.; Karagatzides et al., 1985). *Bryum* spp. are short, compact mosses with a cushion subformation, but *Plagiomnium medium* is a tall, loose moss (Longton, 1988) that contributes to soil development by accumulating deep organic, nitrogen-rich peat over the mineral soil (Russel, 1990). Lichens (Kallio and Kallio, 1975) and anaerobic bacteria (Karagatzides et al., 1985) are unimportant as sources of fixed nitrogen. No legumes were present at the site of past anthropogenic fertilization that might have contributed to biologically fixed nitrogen. The greatest amount of nitrogen fixation in the Arctic occurs in moss associations (Granhall and Lid-Torsvik, 1975).

The distributions of *Salix arctica* and *Saxifraga tricuspidata* on the site of past anthropogenic fertilization were surprising. *Salix arctica*, which is not a plant indicative of nutrient enrichment, grew luxuriantly in Zone B near the entrances to the Thule houses than in less enriched areas downslope and on adjacent "uninfluenced" polar semidesert. *Salix arctica* has one of the widest ranges of tolerance to environmental factors of any arctic plant species (Svoboda, 1977). *Saxifraga tricuspidata*, also not a plant associated with enriched areas, grew in relative abundance on the enriched beach fringe (Zone F) as well as on adjacent "uninfluenced" polar semidesert. Although *Salix arctica* and *Saxifraga tricuspidata* are not found exclusively at nutrient-enriched sites (Forbes, 1996), the growth of these plants probably is enhanced under such conditions (Tank and Kevan, unpubl. data).

Dryas integrifolia was the most common plant species found within the "uninfluenced" polar semidesert. The frequency of this plant decreased as soil depth, nitrogen level, and phosphorus level increased. *Dryas integrifolia* is adapted to growing in nutrient-poor substrates that are relatively warm and dry (Svoboda, 1977; Fetcher and Shaver, 1990).

Unenriched raised beaches are dominated largely by *Dryas integrifolia* (Dansereau, 1954; Svoboda, 1977; Muc et al., 1994). Svoboda (1977) recognized three physical vegetation zones on unfertilized raised beaches on Devon Island, Nunavut. The crest of the beach in Svoboda's study (1977) was dominated by *Saxifraga oppositifolia*, *Carex nardina*, and *Salix arctica*. The beach slope vegetation consisted mostly of *Dryas integrifolia*, with smaller amounts of *Saxifraga oppositifolia*, *Carex rupestris*, and *Carex nardina*. The foot of the beach was dominated by *Dryas integrifolia*, *Carex misandra*, and *Cassiope tetragona*. Although lichens accounted for much of the plant cover on the crest and slope, mosses were more dominant at the bottom of the slope (Svoboda, 1977).

There is a direct relationship between age, elevation, and plant cover on raised beaches in the Canadian Arctic. Young raised beaches (3000–6000 years old) have less vegetational cover than those 6000–9000 years old (Svoboda, 1977). Bliss and Gold (1994) explain the distribution of some High Arctic plant communities through the

TABLE 2. Relative abundance of plant species (%) found on and adjacent to the area of anthropogenic influence at Arnaqquaksaat, Igloolik Island, Nunavut (69°22' N, 81°47' W). Zones B–G represent the "influenced" area, while Zones A and H represent adjacent "uninfluenced" areas. Vegetation zones are shown on Figure 3.

Plant Species	Zone A	Zone B	Zone C	Zone D	Zone E	Zone F	Zone G	Zone H
Cerastium alpinum	0	0	3	0	3	0	0	0
Draba sp.	0	0	2	0	0	0	0.2	0
Dryas integrifolia	21	0	0	0	24	0	0	28
Papaver radicatum	0	0	0	0	0	0	1	0
Pedicularis capitata	0.5	16	0	4.5	0	0	0	0
Polygonum viviparum	0	3	0	2	0	0	0	0.5
Salix arctica	4	42	0	21	0	11	0	5
Salix reticulata	0	0	0	0	0	0	0	3
Saxifraga caespitosa	0	0	3.5	3.5	7.5	0	0	0
Saxifraga cernua	0	0	0	4.5	0	0	0	0
Saxifraga hieracifolia	0	0	0	0	3.5	0	0	0
Saxifraga hirculus	0	4.5	5.5	4	0	0	0	0
Saxifraga oppositifolia	0.5	0	0	0	0	1	0.3	2
Saxifraga tricuspidata	0	0	0	6	4.5	19.5	0	0
Alopecurus alpinus	0	0	0.5	0	2	0	0	0
Arctagrostis latifolia	0	0	0	0.5	2	2	0	0
Poa hartzii	0	7	2	0	1	2	0	0
Dupontia sp. & other grasses	0	18.5	0	0	0	0	1	0
Other	0.5	1	2	5	3	2.5	0	0.5
Bryum sp.	2.5	1	0	46	18	43	10.5	0
Plagiomnium medium	0	0	80	0	27	0	0	0
Lichens	6	1	1.5	1	1.5	0	0	6
Bare ground	65	6	0	2	3	19	87	55

effects of strand enrichment from marine algae and associated cyanobacteria along the shorelines and subsequent isostatic rebound that moved the enrichment upwards. Although the raised beaches in Bliss and Gold's (1994) study are young (3000 years old), Kelly and King (1995) found no correlation between soil development and plant succession on older raised beaches (6790–8920 years old) on Devon Island, Nunavut to support that idea. The raised beach examined in our study is young (700–1000 years old), having a maximum elevation of 11 m above sea level (Rowley, 1997). Successional events associated with isostatic rebound may drive nutrients from the shore up the slope of a raised beach, as described by Bliss and Gold (1994). But such events could be masked by the deposition of large amounts of organic matter during hundreds of years of human habitation along the beach crest and by walrus slaughtering just above the high tide mark at that time. The upslope site of past anthropogenic fertilization is easily distinguished from the adjacent "uninfluenced" polar semidesert on the raised beach by its significantly greater plant cover and soil depth (Table 1). Our study suggests a net flow of total nitrogen downslope to the sea at the site of past anthropogenic fertilization (Fig. 5). Nitrogen is well known to be highly mobile in soil moisture (Stevenson, 1986). Furthermore, the slope of the bank into which the houses were built is quite steep, and the soil is migrating downwards as a result of solifluction (Rowley, 1997).

The gradual change in plant species composition up the slope to the crest of raised limestone beaches in the Canadian Arctic is also related to topographical factors, such as drainage and exposure (Svoboda, 1977; Danks, 1981). It is possible that slight landscape undulations in this site, which are typical of the region generally, could have helped moisture and nutrients to accumulate, resulting in soil development and lush vegetation. Slight variations in topography allow for differences in snow accumulation, which influence the timing of snowmelt, drainage, and soil moisture (Woodley and Svoboda, 1994). Gersper et al. (1980) and Giblin et al. (1991) reported on the close relationships of moisture, pH, substrate quality, and temperature, as well as meso- and microtopographical gradients, on rates of nitrogen cycling. Nitrification and denitrification rates were found to be higher on a drier beach ridge-basin than on a damp sedge meadow on Devon Island, Nunavut (Chapin, 1996). Topographic variations can therefore result in drainage and moisture accumulation gradients that affect nutrient cycling (Babb and Whitfield, 1977) and plant communities (Muc and Bliss, 1977). Poor drainage and cool soil temperatures slow down the microbial decomposition of organic matter, leading to accumulation of peat and higher plant productivity (Widden, 1977; Danks, 1981). The landscape along Igloolik Island's coast is highly dynamic as it continues to rise from the sea by isostatic rebound (Dredge, 1992).

By causing variation in biogeochemical processes, the topography of Arctic landscapes is also a major factor in determining variability of soil pH (Valentine and Binkley, 1992). Haag (1974) explained the lower pH observed in enriched environments as resulting either from nitric acid formation stimulated by microbial nitrification, or from preferential uptake of ammonium ions by plants, which leads to nitrate imbalance. The lowest measures of pH, although only slightly acidic or neutral, were found in the most enriched sites in this study—the upslope area of past anthropogenic fertilization and the soils around bird rock

TABLE 3. Spearman rank correlations for % total plant cover, total nitrogen, sodium bicarbonate-extractable phosphorus, available potassium, available magnesium, and pH on the site of anthropogenic enrichment and adjacent areas of unaltered polar semidesert at Arnaqquaksaat, Igloolik Island, Nunavut, Canada (69˚22′ N, 81˚47′ W).

	Dist	Cov	CCov	N	P	K	Mg	PH	CN	CP	CK	CMg	CpH
Dist	1.00												
Cov	-0.64*	1.00											
CCov	-0.83*	0.93*	1.00										
N	-0.83*	0.35	0.54	1.00									
P	-0.52	0.46	0.40	0.15	1.00								
K	-0.43	0.09	0.09	0.26	0.88*	1.00							
Mg	-0.83*	0.35	0.54	1.00	0.15	0.26	1.00						
pH	0.70*	-0.43	-0.52	-0.94*	-0.10	-0.15	-0.94*	1.00					
CN	-0.14	-0.23	-0.03	-0.03	-0.03	-0.09	-0.03	0.21	1.00				
CP	0.39	-0.40	-0.39	-0.13	-0.42	-0.13	-0.13	0.14	-0.65*	1.00			
CK	-0.17	0.38	0.41	0.20	-0.18	-0.20	0.20	-0.22	-0.70*	0.66*	1.00		
CMg	0.60*	-0.93*	-0.89*	-0.31	-0.33	0.09	-0.31	0.39	-0.09	0.65*	-0.12	1.00	
CpH	0.56	0.02	-0.28	-0.80*	0.33	0.19	-0.80*	0.69*	-0.37	0.14	-0.02	0.12	1.00

* indicates significant differences determined by Spearman Rank Correlations ($p < 0.1$).

(Dist = distance from Thule house entrances; Cov = % vegetative cover on the influenced area; Ccov = % vegetative cover on uninfluenced area; N = total nitrogen (%) on the influenced area; P, K, and Mg = phosphorus, potassium, and magnesium content (mg/L) on the influenced area; pH = soil pH on the influenced area; CN = total nitrogen (%) at the uninfluenced soil sampling sites; CP, CK, CMg = phosphorus, potassium, and magnesium content (mg/L) at the uninfluenced soil sampling sites; CpH = soil pH at the uninfluenced soil sampling sites).

perches. Among the other factors mentioned, humic acids associated with organic matter may have contributed to these lower measurements of pH (Valentine and Binkley, 1992). Moore (1986) also observed lower values of pH in archaeological areas.

Magnesium is one of the major soluble ions in soil (Bohn et al., 1979), especially in areas with limestone bedrock (Millar, 1955). Fine-textured soils tend to contain more magnesium than those with coarse particles because less leaching occurs in finer soils (Millar, 1955). The minor variations in topography may account for the variation we found in magnesium levels. In contrast to the influenced area, the uninfluenced area consisted mostly of broken limestone rocks with little soil. The highest levels of magnesium were found in the soils around bird perch rocks, probably reflecting continual enrichment from feces and bones. We cannot explain the opposing trends in the relationship of soil magnesium content to distance downslope on the influenced versus the uninfluenced areas. In general, the magnesium requirement of plants is low because the element is conserved during growth (Millar, 1955).

Mid- and High Arctic polar semideserts, in the unfertilized state, have very little organic matter, as well as low levels of nitrogen and phosphorus (Svoboda, 1977; Henry et al., 1987; Bliss et al., 1994; Kevan et al., 1995; Forbes, 1996). Low temperatures (Stutz and Bliss, 1975; Svoboda, 1977) and low soil phosphorus concentrations (Basilier, 1974; Chapin et al., 1991) result in low rates of nitrogen fixation. Decomposition of plant and animal remains, urine, and feces would be expected to increase the levels of nitrogen and phosphorus in the soil (Lutz, 1951; Proudfoot, 1976; Moore, 1986; McKendrick et al., 1980; Moore and Denton, 1988; Forbes, 1996). This may have occurred within the site of past anthropogenic enrichment and in the soils around the bird rock perches. Our results showed significantly higher nitrogen and phosphorus concentrations within the upslope area of past human influence and in the animal-enriched soils than in the surrounding unaltered polar semidesert. We did not show a significant difference between nitrogen and phosphorus levels of the upslope area of past anthropogenic fertilization and those measured in the soils around the bird rock perches, indicating similar levels of enrichment. It is likely that since the end of human occupation in the upslope site, ongoing mammal and bird activity has continued to contribute to the nutrient loading in localized areas, especially at the ruined houses, where there are many lemming burrows.

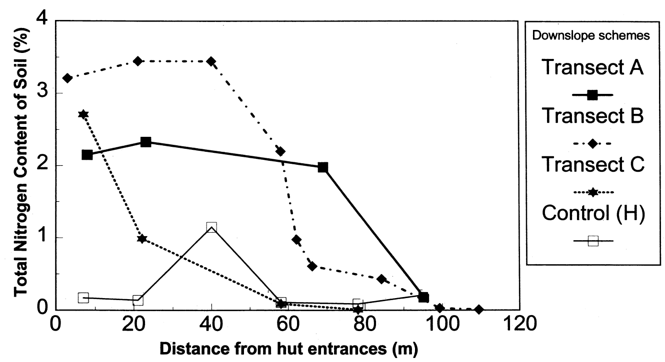

FIG. 5. Distance from Thule house entrances (m) versus total nitrogen content of soil (% by dry mass) on the area of anthropogenic influence at Arnaqquaksaat, Nunavut, Canada.

Porsild (1955) noted the importance of nutrient contributions from owl perches, animal burrows, and archaeological sites to the Arctic ecosystem. Phosphorus inputs tend to be very persistent because of the element's low solubility and slow movement through the soil (Proudfoot, 1976). This may explain our finding that enriched soils at the site of past human influence (upper area) and around the bird perch rocks had phosphorus concentrations five to seven times higher than those on the unaltered polar semidesert. The effects of phosphorous on nitrogen fixation, along with topographical effects, especially in areas of anthropogenic and natural enrichment contribute to the development of micro-oases in an otherwise scarcely vegetated polar semidesert (see also Muc et al., 1994).

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