ARCTIC
VOL. 61, NO. 2 (JUNE 2008) P. 199–211

Environmental Conditions and Vegetation Recovery at Abandoned Drilling Mud Sumps in the Mackenzie Delta Region, Northwest Territories, Canada

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(*Received 12 February 2007; accepted in revised form 17 October 2007*)

ABSTRACT. Historical data from oil and gas exploration in the delta of the Mackenzie River, Northwest Territories, in the 1970s provided an opportunity to estimate decadal-scale impacts of exploratory oil and gas drilling on native plant communities in low Arctic tundra. We assessed changes in vegetation composition and associated environmental gradients across seven drilling mud sumps in the Kendall Island Bird Sanctuary, Mackenzie Delta. Three decades after disturbance, drilling sumps had developed vegetation coverage equivalent to that in undisturbed areas, although bare soil persisted in ponded areas and where a salt crust was present. Vegetation on sumps was composed of communities dominated by forbs, grasses, and tall shrubs that were distinct from adjacent, undisturbed sedge and low shrub communities. The area of altered vegetation around a sump was generally larger in upland or saline environments than in lowland areas. Pooled water observed around many sumps was likely associated with thaw subsidence that occurred following construction, which was subsequently compounded by snow drifting and increased soil temperatures along the margins of the sump mound. Changes in drainage, active-layer depth, and surface salt concentrations appear to be key environmental factors that have helped shape plant communities established on drilling sumps in the three decades after disturbance.

Key words: disturbance, drilling mud sumps, low Arctic tundra, Mackenzie River delta, oil and gas exploration, permafrost, plant communities, vegetation classification

RÉSUMÉ. Les données historiques relatives à l'exploration pétrolière et gazière réalisée dans le delta du fleuve Mackenzie, Territoires du Nord-Ouest, dans les années 1970 ont permis d'estimer les incidences décadaires des forages pétroliers et gaziers exploratoires sur les peuplements de végétaux régionaux de la basse toundra arctique. Nous avons évalué les changements caractérisant la composition de la végétation et les gradients environnementaux connexes relativement à sept bassins à boue du refuge d'oiseaux de l'île Kendall, dans le delta du Mackenzie. Trois décennies après la perturbation, la couverture végétale des bassins à boue était équivalente à celle des endroits non perturbés, bien qu'il restait toujours du sol dénudé dans les endroits en présence d'étangs et de croûtes salées. Le végétation se retrouvant sur les bassins était composée d'herbes non graminéennes, de graminées et de grands arbrisseaux différents des peuplements adjacents constitués de laiche et de petits arbrisseaux non perturbés. La zone caractérisée par la nouvelle végétation autour d'un bassin était généralement plus volumineuse dans les hautes terres ou les milieux salins que dans les basses terres. L'eau accumulée autour de nombreux bassins découlait vraisemblablement de la subsidence attribuable au dégel qui s'est manifesté après la construction, ce qui a été aggravé par la poudrerie et les températures du sol à la hausse le long des marges du monticule des bassins. Les changements en matière de ruissellement, de profondeur de la couche active et de concentrations de sel de surface semblent constituer d'importants facteurs environnementaux ayant aidé à façonner les peuplements de végétaux qui se sont établis sur les bassins de forage au cours des trois décennies ayant suivi la perturbation.

Mots clés : perturbation, bassins à boue de forage, basse toundra arctique, delta du fleuve Mackenzie, exploration pétrolière et gazière, pergélisol, peuplements de végétaux, classification de la végétation

Traduit pour la revue *Arctic* par Nicole Giguère.

INTRODUCTION

Resource exploration and extraction in Arctic regions can lead to important human impacts on the integrity of Arctic ecosystems. Terrestrial vegetation and soils in Arctic tundra are generally slow to recover from human disturbances, and the physical impacts of development on plant communities can persist for decades or centuries (e.g., Forbes et al., 2001). With an increase in hydrocarbon exploration and the proposal to develop the Mackenzie Gas Project in the Canadian North (Imperial Oil Resources Ventures Limited, 2004), government agencies, corporations, and local residents are seeking to understand and to find ways to mitigate or reduce the impacts of development. This creates a strong need for scientific information on long-term ecosystem responses to disturbance in the

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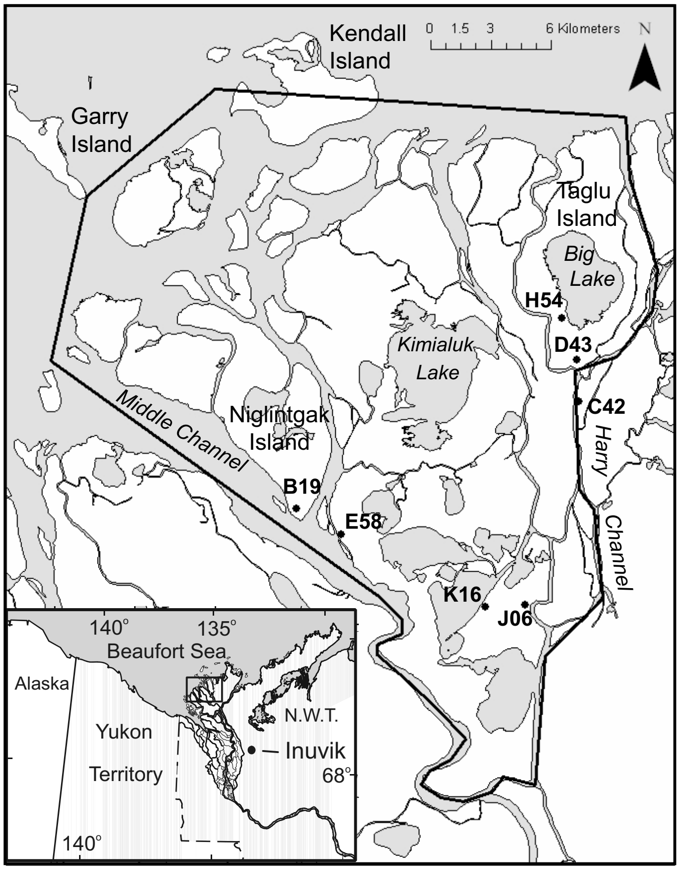

FIG. 1. Map showing location of sump study sites within the Kendall Island Bird Sanctuary (outlined polygon) in the outer Mackenzie River delta, Northwest Territories, Canada.

Arctic and the factors that affect the pattern and rate of ecosystem recovery.

Since the early 1970s, over 150 exploratory hydrocarbon wells have been drilled in the Mackenzie Delta region, including at least 19 in the Kendall Island Bird Sanctuary (Fig. 1). In accordance with land-use regulations, the drilling mud generated by hydrocarbon exploration was disposed of in sumps excavated in permafrost (French, 1980). Typically, potassium chloride was added to depress the freezing point of the mud when drilling through permafrost and to maintain the integrity of shale formations encountered at greater depth. When operations were complete, the drilling fluid, cuttings, and rig wash were deposited in the sump and capped with the excavated materials to create a low mound. It was intended that permafrost would establish and immobilize the capped drilling waste. Several decades after drilling, the integrity of the sump caps and disturbance to surrounding terrain are variable, and this variation is likely related to the nature of the operation, abandonment practices, and local environmental conditions (Kokelj and Geonorth Ltd., 2002).

Observations of recovery from previous oil and gas exploration in the Mackenzie Delta provide an important opportunity to assess longer-term impacts of hydrocarbon development on alluvial and upland habitats within coastal low Arctic tundra. Results from surveys of vegetation recovery following sump construction provide an indication of the persistence of environmental and ecological effects associated with such disturbances. In addition, patterns of vegetation cover may influence the ground thermal conditions that affect the long-term integrity of the sump cap. In this paper, we document patterns of vegetation composition on historical drilling sumps after three decades of recovery and assess how patterns of plant cover relate to gradients in soil, active-layer, and snow conditions on and around the sump caps. On the basis of these observations, we identify key interactions likely to influence the ecological recovery of a sump and suggest some site conditions or development practices that may influence the sensitivity of coastal tundra to oil and gas development activities.

STUDY AREA

The Kendall Island Bird Sanctuary is located in the northeastern portion of the outer delta of the Mackenzie River. The sanctuary is bounded by Mackenzie Bay to the north, Harry Channel to the east, and Middle Channel to the south and west (Fig. 1). Low-lying alluvial deposits comprise much of the terrestrial environment. Permafrost thickness ranges from only a few meters beneath aggrading point bars to several hundred meters under alluvial terrain near Taglu Island (Taylor et al., 2000). Ice wedges and aggradational ice can account for 30% to 40% of the volume of the top meter of permafrost (Mackay, 1963; Kokelj and Burn, 2005a). Alluvial terrain in the outer Mackenzie Delta can be inundated by spring flooding and extreme summer storm surges (Mackay, 1963). Willows and alders grow on aggrading point bars, whereas sedges and mosses dominate the poorly drained wetlands away from the stream channels (Mackay, 1963). Active-layer thickness ranges from about 60 cm in sedge wetlands to more than 120 cm in willow communities on aggrading point bars (Tarnocai et al., 2004).

Upland environments in the Kendall Island Bird Sanctuary are erosional remnants of the Tununuk Low Hills and consist of tills and glaciofluvial sediments rich in ground ice (Mackay, 1971; Rampton, 1988). The permafrost is several hundred meters thick (Taylor et al., 2000). Vegetation is primarily upland low-shrub tundra dominated by ericaceous shrubs and dwarf birch on hummocky terrain. Active-layer thickness at undisturbed sites ranges from 30 to 90 cm (Mackay and Burn, 2002).

The coastal climate measured at Tuktoyaktuk, to the east of the Mackenzie Delta, is characterized by cold winters up to eight months in duration and short, cool summers due to the persistence of sea ice in early summer (Burn, 2002). Mean January temperature is -27.2˚C and mean July temperature is 10.9˚C. Late winter snow depths at Tuktoyaktuk are less than 40 cm (Environment Canada, 2005). Local patterns of snow accumulation are related to topography or vegetation because winds redistribute the snow (Mackay and MacKay, 1974).

TABLE 1. Study sites used for surveys of vegetation and environmental conditions in 2005. Spud date marks the start of drilling at the wellhead, and rig-release date, the removal of the drilling rig from the site. Sample size for each site is the sum of the vegetation sample points in three zones (n = cap + perimeter + undisturbed control).

Site	Location	Spud Date	Rig Release	Terrain Type	Undisturbed Vegetation Type	Vegetation Sample Size by Zone
C42	69.3514°N, 134.9472° W	30 April 72	18 November 72	Alluvial	wet sedge	n = 4 + 8 + 8
H54	69.3889° N, 134.9683° W	2 December 76	5 April 77	Alluvial	wet sedge and wet shrub	n = 5 + 7 + 8
D43	69.3705° N, 134.9501° W	23 March 73	11 September 73	Alluvial	wet sedge and wet shrub	n = 8 + 3 + 15
B19	69.3031° N, 135.3053° W	18 October 75	22 February 76	Alluvial	saline marsh	n = 5 + 14 + 10
E58	69.2915° N, 135.2487° W	28 February 77	8 June 77	Alluvial	wet sedge	n = 7 + 8 + 7
J06	69.2600° N, 135.0161° W	24 November 73	16 May 74	Upland	shrub heath	n = 3 + 6 + 6
K16	69.2591° N, 135.0662° W	24 February 75	13 July75	Upland	shrub heath and wet sedge	n = 5 + 8 + 4

Seven drilling mud sumps were selected for detailed investigation (Fig. 1). The sump sites were located either in uplands or in lowland alluvial terrain (Table 1). Of the seven sumps we studied, four were located in lowland wet sedge or wet shrub tundra, one in lowland saline marsh, and two in upland shrub heath tundra (Table 1). Lowland sites were generally characterized by the presence of ice-wedge polygons in undisturbed terrain and by frequent flooding with poor drainage. Upland sites had hummocky terrain and were moderately well drained. All of the sumps were constructed between 1972 and 1977 (Table 1) and were approximately 30 years old when surveyed for this study. One sump, J06, was treated in the summer after construction with a single dose of NPK fertilizer and a seeding application of non-native grass seeds (Younkin and Martens, 1976). The seeded grasses included mixed and single-species plots of *Agrostis* spp., *Alopecuris pratensis*, *Festuca rubra*, *Poa pratensis*, and *Phleum pretense*.

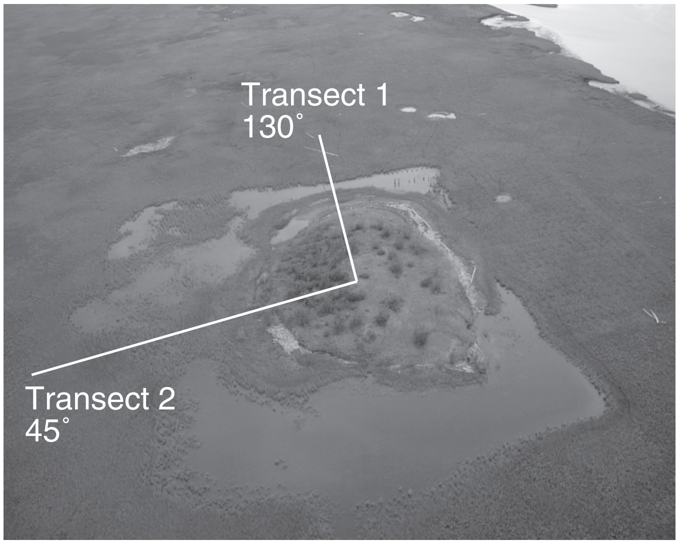

FIG. 2. Oblique aerial photo showing Sump E58 and the approximate location of sampling transects. Transect orientations are shown as compass orientations without correction for declination. Pilings are present around the SE and SW sides of the sump.

METHODS

Field Measurements

Data on plant community composition and environmental conditions were collected across transects laid out from the center of the sump cap into surrounding undisturbed tundra. Field data were collected in late July 2005, except for snow observations made in April 2006. Vegetation surveys consisted of measurements of species cover, canopy height, and leaf area index (LAI) along one or two linear transects (Fig. 2). Each transect started in the center of a sump cap, crossed the sump cap and perimeter, and ended in undisturbed tundra. We avoided placing transects where they would cross into other disturbed areas within the drilling lease and focused specifically on the sump disturbances. Vegetation sample points were randomly located within 10 m intervals across a total length of 100–170 m per transect. At the five lowland sites, two perpendicular transects were used for sampling, while the larger disturbed areas of the upland sites were sampled along a single, linear transect. Sample points were classified in the field as belonging to one of three zones: a) sump cap, consisting of the elevated portion of the sump where the soil overburden was placed; b) sump perimeter, the areas around the edge of a cap, consisting of depressions or gentle slopes below the sump cap; or c) undisturbed tundra, consisting of intact vegetation that showed no evidence of disturbance. A total of 15 to 29 points at each site were sampled for vegetation (Table 1).

At each sample point, plant community composition was described by visual cover estimates made in 100 × 100 cm quadrats. Cover was estimated separately for each vascular plant species in the plot, except that *Salix* spp. (willows) were grouped together into three size classes (< 30 cm, 30–100 cm, > 100 cm). The same person performed all cover estimates and assessed the living portions of the aboveground vegetation. Dead vegetation that was attached or fallen was included in a separate “litter” category. Species were identified in the field, and for species of uncertain identity, voucher specimens were collected to be identified later in the laboratory. Species nomenclature followed Porsild and Cody (1980). Cover of five general categories—moss, lichen, bare soil, water, and wood debris—was also estimated. Plant canopy cover was calculated as the sum of individual cover values for all vascular plants in a plot. Other aspects of vegetation structure were characterized by observations of maximum canopy height, LAI (using a LAI2000 meter, LI-COR Biosciences, USA), and depth of the organic layer in each quadrat. The organic layer was defined as non-mineral soils of well- to partially decomposed organic material, excluding undecomposed surface litter.

Soil chemistry, site elevation, depth of thaw, and snow depth were measured along the vegetation transects to provide information on environmental conditions across the sumps and undisturbed surroundings. An elevation cross-section was leveled along each transect relative to the surface of the closest river channel. Active-layer depths were determined at vegetation sample points by pushing a calibrated steel probe into the soil to the depth of refusal. Soil samples from the top mineral horizon and at the bottom of the active layer were taken with a 5 cm diameter soil corer at one or more locations within the sump cap, perimeter, and adjacent undisturbed terrain at each site. Samples were stored in a cool, dark place and were analyzed one week after collection. The sites were revisited in early April 2006, when snow depths (cm) were measured at 10 m intervals along the sample transects by pushing a calibrated dowel into the snow pack to the depth of refusal.

Soil samples were analyzed for particle size distribution, gravimetric moisture content, organic matter content, pH, electrical conductivity (EC) of pore water, and water-soluble ions, following McKeague (1978). Soil pH was determined on saturated paste extractions. Samples of pore water extracted from the soil samples were analyzed by ion chromatography. The sodium adsorption ratio (SAR) was calculated as:

$$\mathrm{SAR} = \frac{[\mathrm{Na}^+]}{\sqrt{\frac{1}{2}\left([\mathrm{Ca}^{++}]+[\mathrm{Mg}^{++}]\right)}}$$

where ionic concentrations are in meq/l. SAR values greater than 13 indicate sodic soils, whereas EC values greater than 4 dS/m indicate that the soil is saline. If both values are exceeded, the soil is classified as saline-sodic (Brady and Weil, 1999).

Statistical Analysis

The categorical effects of disturbance zones on vegetation characteristics (species richness, cover of plant growth forms, LAI, and canopy height) and environmental conditions (snow depth, active-layer depth, soil chemistry) were examined qualitatively by comparing means and standard errors across disturbance zones at each site. We plotted vegetation and environmental variables at 10 m increments along each transect to provide an assessment of the spatial covariance in these variables across a sump.

Examining the responses of vegetation communities to an underlying gradient poses the challenge of evaluating simultaneous changes in abundance of multiple, potentially interacting species (McCune and Grace, 2002). We used multivariate techniques of ordination and cluster analysis to assess how vegetation composition in the Mackenzie Delta responded to environmental and disturbance gradients associated with abandoned drilling sumps. Species cover data were summarized in a sample plot × species matrix, and multivariate analyses were performed using the statistics program PC-ORD (v.4, McCune and Mefford, 1999). To reduce noise in the analyses, species observed in only a single plot were deleted from the data set. The cover data were square-root transformed and then standardized by the maximum cover observed for each species, so that rare and abundant species were weighted equally in the multivariate analyses.

We used nonmetric multidimensional scaling (NMS) as an ordination method to extract the dominant patterns of variation in species abundance across sample plots. This ordination approach was selected because it is generally able to produce robust and interpretable results even when relationships among variables are nonlinear (McCune and Grace, 2002). NMS calculations were performed using Sørensen (city-block) distances, random starting configurations, and 40 independent, iterative runs with the data. The optimal number of ordination axes was assessed using a Monte Carlo procedure that compared runs with real versus randomized data. Post-hoc estimates of the amount of variation in the original data set represented by each axis were generated by regressions of Sørensen distances in the ordinated data against Euclidian distances in the original data (McCune and Grace, 2002).

Rank correlations (Kendall's τ) between environmental gradients and ordination axes were used to assess correlations between patterns of plant composition and variations in environmental factors. Candidate environmental variables included relative elevation (standardized as meters above the minimum elevation observed at each site); snow depth; active-layer depth; distance of the sample plot from the cap center; cover of bare soil, moss, water, or litter; and organic layer depth. To characterize soil conditions, we included measures of carbon loss-on-ignition (LOI), percent water saturation, electrical conductivity, and ionic concentration (meq/100 g soil) of water soluble potassium (K^+), chloride (Cl^-), and sodium (Na^+) for samples taken from the top of the mineral horizon. Correlations of environmental gradients with ordination axes were plotted as a vector overlay on the NMS ordination.

Hierarchical cluster analysis was used to identify groups of sample plots that had similar species composition. Hierarchical clustering used Sørensen distances and a flexible beta linkage of β = -0.5, selected from several trials as leading to a space-conserving clustering that minimized single-sample additions to groups. The resulting dendrogram was plotted against the Wishart Objective Function and cut at a level of approximately 50% information remaining to generate community groupings that were separated by large distances and had a biological interpretation consistent with existing classifications of tundra vegetation (e.g., Gould et al., 2003). Indicator species analysis was then used to identify species that consistently differed in their abundance between groups (Dufrêne and

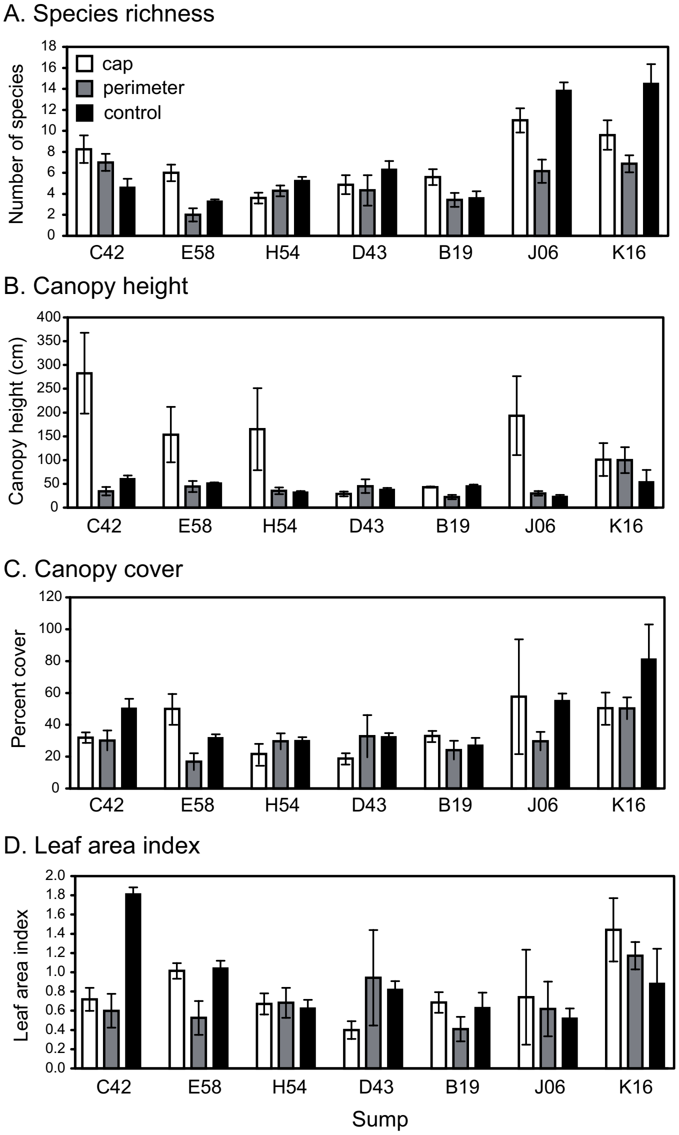

FIG. 3. Variation across sites and disturbance zones (mean ± SE) in general plant community characteristics: A) species richness, or the total number of observed species per plot (m^2); B) mean maximum canopy height in cm; C) percent canopy cover; and D) leaf area index. Bars differentiate the three zones within each site; sump cap (white), perimeter (grey), and undisturbed control zone (black). Sample sizes are listed in Table 1.

Legendre, 1997). Indicator values for each species were calculated from the relative abundance and frequency of the species in each group. Randomization trials with 500 iterations were used to identify indicator species with a low probability of obtaining an equal or higher indicator value by chance ($p < 0.05$).

RESULTS

Vegetation Characteristics across Disturbance Zones

A total of 149 vegetation plots were sampled at the seven sump sites. Four plots located on sump caps and perimeters were covered only by bare soil or water. These plots were excluded from the plant community and ordination analyses, but were included in other vegetation summaries. Vegetated plots comprised 37 samples on sump caps, 50 in sump perimeters, and 58 in undisturbed terrain around the sumps (control zones). Plant observations noted 89 species of vascular plants, plus the three size classes of *Salix* that represent an undetermined number of species. Mosses were present at all sites and lichens were encountered in the undisturbed zones of the two upland sites (K16 and J06). Although total species richness (the number of vascular plants found in each zone) did not vary consistently between zones at the different sites (Fig. 3A), relatively few species (28 species) had distributions that included both sump caps and undisturbed zones. Approximately half (47) of the species encountered were never found on sump caps, and 17 of the species found on caps were never found in control zones. Many of the plants that were restricted to undisturbed areas or sump perimeters were hygric or semi-aquatic species unlikely to survive on the elevated sump caps. These included several species of *Carex* and *Eriophorum* sedges, and herbs such as *Pinguicula vulgaris* and *Ranunculus aquatilis*. Plants that were restricted to sump caps included some grasses (such as *Poa glauca*, *Deschampsia caespitosa*, and *Trisetum spicatum*) and several ruderal herbs (such as *Epilobium angustifolium*, *Artemisia tilesii*, *Matricaria ambigua*, and *Castilleja elegans*). Tall *Salix* shrubs (> 1 m) were also found only on sump caps or perimeters. Comparisons of average plant canopy height indicated plant canopies were substantially taller on sump caps than on control zones at several sites (Fig. 3B).

Although species distributions differed across sump caps, perimeters, and control zones, total plant canopy cover and leaf area index did not show consistent differences between zones (Fig. 3C–D). Average plant canopy cover within control zones ranged from approximately 30% to 80%, and canopy cover in sump cap and perimeter zones substantially overlapped this range. Sites C42 and D43 were the only sites in which measures of both cover and LAI were lower on sump caps than on control zones.

Plant community composition, as summarized by the cover of different plant growth forms, showed consistent differences between disturbance zones (Fig. 4). Grass cover was higher and sedge cover was lower on all sump caps and most perimeters than in undisturbed control zones. Cover of *Salix* and *Alnus* shrubs was noticeably higher on caps at some sites (E58, H54, and J06), but was often lowest in the perimeter zone. The control zones of the two upland sites (J06 and K16) had substantial cover of other shrubs, particularly evergreen species and deciduous dwarf shrubs, but in their cap and perimeter zones, cover of these species was greatly reduced or absent. Differences between zones in the total cover of herbs and moss were variable and site-specific (Fig. 4).

Across an individual sump, patterns of vegetation structure and topography were reflected in patterns of winter snow accumulation and depth of the active layer (Fig. 5).

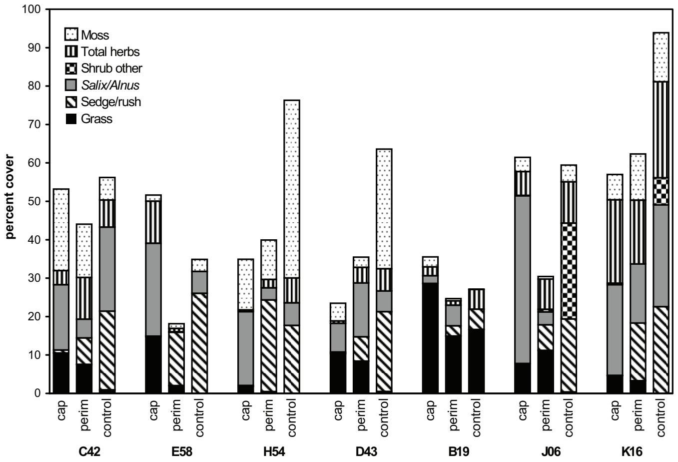

FIG. 4. Variations in percent cover of different plant growth forms across sites and disturbance zones. Percent cover averaged across plots within a zone is shown for six plant growth forms: moss, total herbs (all herbaceous plants except graminoids), shrub other (woody shrubs other than *Salix* and *Alnus*), *Salix* and *Alnus* shrubs, sedges and rushes, and grasses. Total plant cover for each zone (sump cap, perimeter, or undisturbed control zone) is the sum of these six cover values.

Sumps with caps that supported a tall vegetation canopy of alders or willows (e.g., C42, E58, H54) showed maximum snow depths close to the cap center. Deep accumulations of snow were also found along the sump perimeters in association with cap topography (Fig. 5). With increasing distance from the sump, snow accumulation became less variable, shallower, and similar in depth to the height of the low shrub or herbaceous canopy. Depth of thaw was greater in sump cap and perimeter zones than in the surrounding undisturbed tundra.

Soils

Alluvial and quaternary deposits in the outer Mackenzie Delta were derived largely from carbonate and shale parent materials; thus, Ca^{++} tends to be a dominant soluble cation in the weakly acidic to alkaline mineral soils (Table 2) (Rampton, 1988; Kokelj and Burn, 2005b). Typically, concentrations of soluble sodium and chloride in soil porewater were less than 60 mg/l, but near B19, where incursions of seawater during storm surges have salinized the alluvial terrain, background concentrations were an order of magnitude greater ($Na^+ = 2771$ mg/l; $Cl^- = 5824.5$ mg/l) (Table 2). Although the soils around B19 are naturally saline, saline-sodic soils at the edges of B19 suggest that drilling fluids are contributing to the conditions adjacent to the sump.

Discrete pockets of saline soils, conspicuous because of their sparse vegetation cover, were identified on the perimeter of the upland sumps (J06 and K16). Soluble-chloride concentrations of more than 7500 mg/l were measured in the soil of these areas and have likely inhibited plant growth. Soil salinization was least evident around the perimeters of alluvial sumps that were outside of the influence of seawater incursions (E58, D43, H54, C42). Over time, spring flooding may leach most salts from saturated soils around these sumps. Nevertheless, even these areas had maximum perimeter Cl^- concentrations ranging from 116 mg/l at H54 to 674 mg/l at E58, and these levels were generally higher than the maximum concentrations in their respective control areas (53 mg/l at H54 to 150 mg/l at E58).

Calcium and Mg^{++} concentrations in sump cap soils are slightly greater than background concentrations and are likely derived from the thawed permafrost that constitutes the cap materials (Table 2) (Kokelj and Burn, 2005b). A salinized area ($Na^+ = 1053$ mg/l; $Cl^- = 2058$ mg/l) on the sump cap of D43 is almost certainly of anthropogenic origin. It is likely to persist because the cap is well above the level of flooding, so flushing of salts is minimal (Table 2).

Variations in Vegetation Composition

Ordination of the species cover data resulted in a three-dimensional solution that captured 67% of the variation in the original data set. A plot of the two primary-axis scores (representing 23% and 27% of variation in the data set, respectively) shows that samples from sump caps tend to occupy a distinct region of ordination space with respect to samples from undisturbed terrain (Fig. 6). Similarly, the hierarchical clustering procedure divided the 145 vegetated plots into seven main community types that clearly identified a single group associated with sump caps (Group 1, Fig. 7). Within the cluster analysis, samples from sump perimeters were dominant within two vegetation groups (4 and 5), and the four remaining groups were composed of samples largely found in undisturbed tundra (Fig. 7). In the ordination analysis, the distribution of sump perimeter samples showed extensive overlap with both cap and control samples, indicating the apparent intermediate nature of the perimeter plots (Fig. 6).

Correlations of environmental variables with the compositional variation represented by the ordination axes indicated that samples from sump caps tended to occur in areas with deeper active layers and, not surprisingly, at locations closer to the sump center and at higher elevations, with less cover of standing water (Fig. 6; Table 4). Hierarchical clustering of the disturbed cap group indicated a subgroup dominated by *Calamagrostis canadensis* (bluejoint grass) and a second subgroup dominated by mixed grasses and forbs (Fig. 7). The *Calamagrostis* subgroup frequently included the herbs *Castilleja elegans* and *Gentiana propinqua* (Table 3), and was found primarily on sump caps in alluvial areas around Niglintgak Island (E58 and B19). Composition of the mixed grass-forb subtype included the grasses *Arctagrostis latifolia* and *Calamagrostis purpurescens*, and the herbs *Parnassia palustris*, *Matricaria ambigua*, and *Artemisia tilesii.*

Other community types that occurred primarily within the disturbed zones of the sumps were the mesic shrub-forb type (group 5) and the moist saline type (group 4, Fig. 7). Most samples in the mesic shrub-forb type were from sump perimeters and caps and were associated with

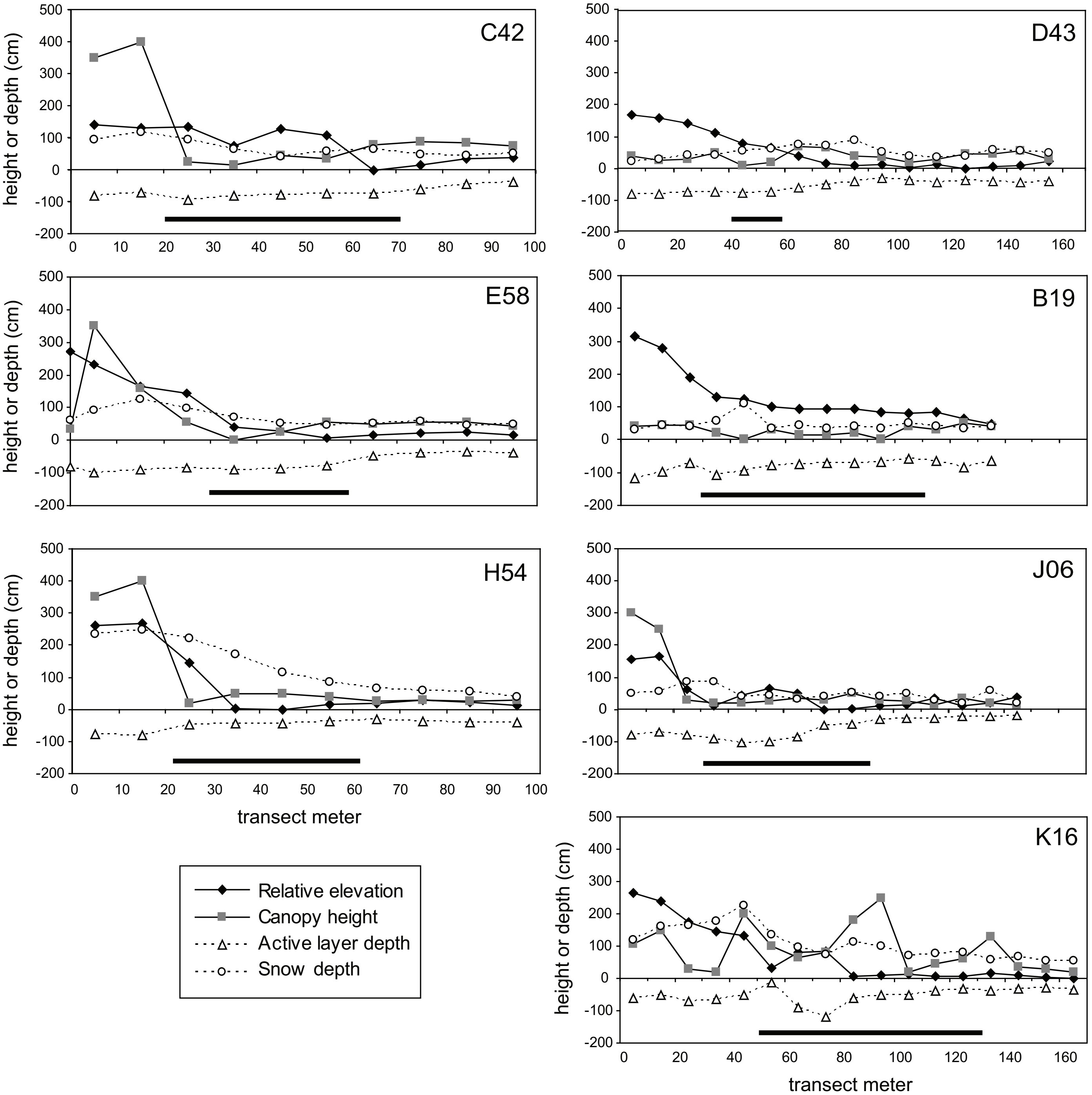

FIG. 5. Spatial patterns in plant community structure (maximum canopy height) and environmental variables (relative elevation, active-layer depth, and snow depth) along transects measured from the sump cap into undisturbed tundra at each of the seven study sites. Data from one transect per site are shown. The location of the sump perimeter for each transect is shown as a black bar along the x-axis; note that the x-axis scale differs between the left and right columns of graphs.

high cover of mosses, moderate elevations, and low Na^+ concentrations in the ordination analysis (Fig. 6). This group was characterized by higher abundance of *Equisetum arvense* and mid-stature *Salix* spp., and frequently included the herbs *Primula egaliksensis*, *Cerastium alpinum*, and *Epilobium angustifolium*, and the grass *Poa glauca* (Table 3). The second, moist saline group was primarily found in perimeter zones with frequent bare soil and high levels of soil salt concentrations. Many of the species that characterize this group (Table 3) are known to be salt-tolerant, such as the grasses *Puccinellia borealis* and *Dupontia fisheri,* and the herb *Ranunculus cymbalaria* (Porsild and Cody, 1980).

Hierarchical clustering also identified an additional group of salt-tolerant vegetation, saline marsh, which was found only in undisturbed alluvial tundra on Niglintgak Island (Figs. 6, 7). This group was specifically associated with the undisturbed zone surrounding sump B19, where

TABLE 2. Summary of soil chemistry and soil soluble ionic concentrations in zones of undisturbed terrain, sump perimeters, and sump caps, Kendall Island Bird Sanctuary, outer Mackenzie Delta.

		Conductivity dS/m at 25˚C	Moisture % dry weight	pH	Ca^{++} mg/l	Mg^{++} mg/1	K^{+} mg/1	Na^{+} mg/1	Cl^{-} mg/l	SAR[1]
Undisturbed	Median	0.7	124.0	7.7	103.0	23.0	7.8	27.5	56.5	0.5
	Mean	2.4	172.0	7.4	206.6	65.4	12.0	312.1	664.8	2.7
	SD	4.5	183.6	0.6	258.0	119.1	13.9	784.8	1657.3	5.5
	Max	16.0	735.0	8.1	933.9	439.0	43.0	2770.9	5824.5	18.8
	Min	0.2	40.0	6.0	27.3	6.6	1.2	11.5	15.9	0.3
Perimeter	Median	1.2	44.5	7.7	141.0	31.0	3.9	98.5	217.1	1.5
	Mean	3.7	81.7	7.7	366.8	97.1	197.2	305.0	1139.5	3.0
	SD	5.1	82.3	0.6	502.6	186.1	677.2	537.5	2108.0	3.4
	Max	20.3	362.0	10.7	2124.2	870.7	3620.7	2885.4	8648.5	13.9
	Min	0.6	22.0	6.4	69.7	0.2	1.2	20.2	45.9	0.4
Sump Cap	Median	1.1	30.0	7.9	175.2	29.7	7.8	49.2	53.0	1.0
	Mean	2.5	32.3	7.9	366.1	82.1	9.1	131.3	218.2	1.6
	SD	5.2	11.1	0.2	768.7	208.9	8.8	251.5	470.7	1.2
	Max	22.9	62.0	8.1	3386.8	954.6	31.3	1053.4	2058.0	4.2
	Min	0.4	12.0	7.3	49.7	0.0	1.2	13.3	0.0	0.5

[1] SAR = sodium absorption ratio.

abundant driftwood provided evidence of flooding. The saline marsh community occupied a region of ordination space similar to that of the moist saline group, but was dominated by shallow-water species such as *Arctophila fulva*, *Ranunculus aquatilis*, and *Hippuris vulgaris* (Table 3) (Porsild and Cody, 1980).

Two vegetation groups, wet sedge and wet shrub, included the majority of plots found in undisturbed, lowland tundra (Fig. 7) and occupied adjacent areas of the ordination space (Fig. 6). The wet sedge group had a high abundance of semiaquatic sedges and was composed of two subgroups, one dominated by *Carex aquatilis* and the other by *Eriophorum angustifolium* (Table 3). Within the undisturbed alluvial terrain, wet sedge communities occurred in flat, poorly drained areas with abundant free water, and wet shrub communities dominated terrain that was slightly elevated, such as the ridges of ice-wedge polygons or mossy mounds. The wet shrub group was characterized by increased cover of low-stature *Salix* spp. and *Equisetum variegatum*, and frequent occurrences of *Eriophorum scheuchzeri*, *Pinguicula vulgaris*, and *Pedicularis sudetica* (Table 3).

Undisturbed vegetation at the two upland sites (J06 and K16) was largely classed within the shrub heath vegetation type (group 7, Fig. 7). This group was dominated by a diversity of low-stature woody shrubs, such as *Vaccinium uliginosum*, *Dryas integrifolia*, *Rubus chamaemorus*, and *Betula glandulosa* (Table 3). The shrub heath group occupied a relatively large region of ordination space that was associated with high moss cover, thicker organic layers, and abundant moisture (Fig. 6, Table 4).

DISCUSSION

Thirty years after disturbance, intact sump caps are elevated surfaces characterized by well-drained mineral soils with thick active layers. Natural colonization of sump caps has resulted in a level of vegetation cover similar to that observed in native tundra, but with a plant community composition that is notably distinct from that of surrounding undisturbed areas. The main differences are a lesser abundance of sedges and greater cover of grasses on the sump caps, but a greater percent cover of tall deciduous shrubs was also evident in the disturbed areas of some sumps.

The presence of a distinct flora on sump caps indicates that the disturbance generates a unique local habitat for colonizing plant species. Species restricted to the elevated sump caps tended to be forbs or grasses found at very low abundance in undisturbed tundra or locally common in natural disturbances such as river bars or thermokarst slumps (Hernandez, 1973; Porsild and Cody, 1980). Many of the species commonly found on the sump caps or perimeters, such as *Alopecurus alpinus*, *Arctagrostis latifolia*, *Artemisia tilesii*, and *Poa glauca*, have also been listed as common colonizers of gravel or drilling pads in the coastal tundra of Alaska (McKendrick, 1987; Jorgenson et al., 2003). The excavated permafrost sediments used as sump cover materials are likely to provide a poor source of plant propagules for regeneration, and vegetative spread of rhizomatous plants from undisturbed tundra onto the elevated and dry sump cap is unlikely. Consequently, most plant colonization of the sumps has probably occurred via dispersed plant seeds (Forbes et al., 2001).

Only one site in our study, J06, received a seeding treatment to promote revegetation after sump abandonment. Despite the successful establishment of several non-native grasses at the site in the two years after the seeding treatment (Younkin and Martens, 1976), we failed to encounter any non-native species in our plots in 2005 (30 years after seeding). Although inconclusive, this fact suggests that non-native species are unlikely to persist in high abundance following several decades of succession on seeded sumps.

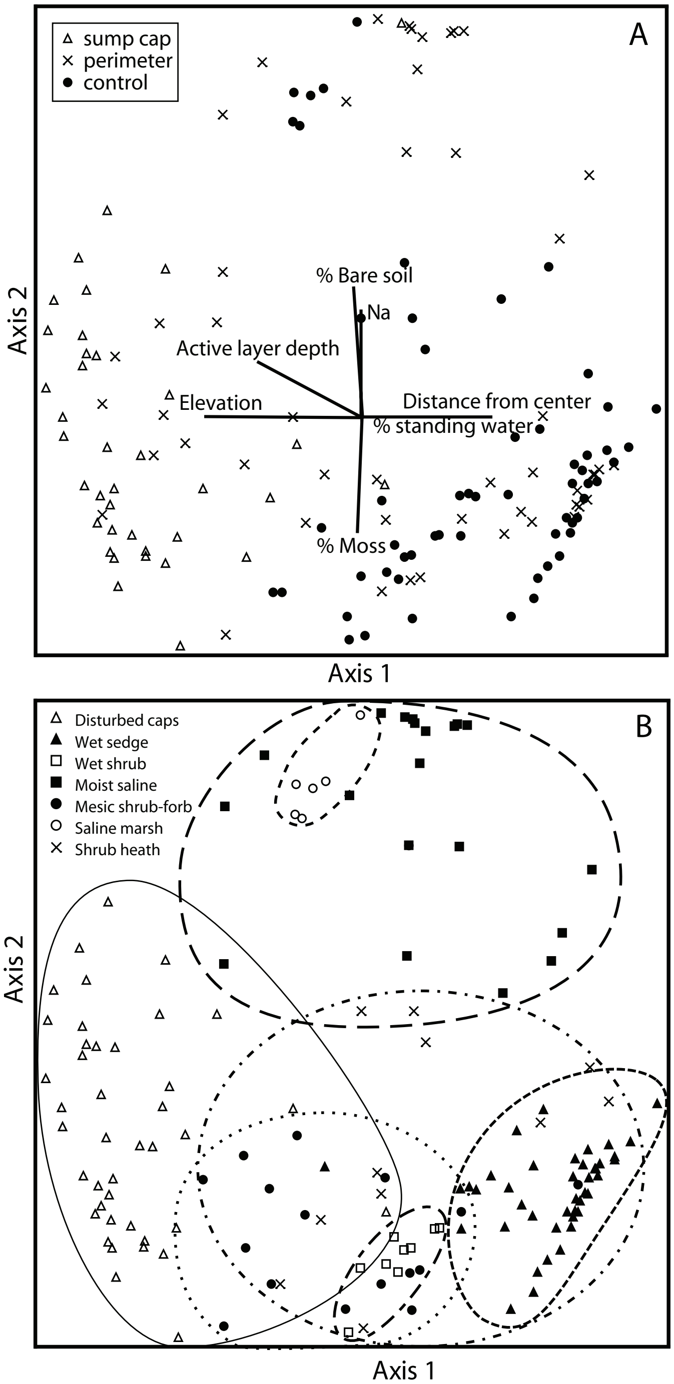

FIG. 6. Distribution of samples of vegetation cover plotted on the first and second axes of a three-dimensional NMS ordination. The NMS ordination used 160 iterations to produce a solution with a final stress of 17.7 and instability of 0.00001. The ordination axes have been rotated to align Axis 1 with the strongest environmental gradient. A) Symbols indicate whether plots were located on sump caps (open triangles), perimeters (crosses), or undisturbed controls (solid circles). Line vectors indicate the strength and direction of correlations ($\tau > 0.35$) of axis scores with the labeled environmental variables (see Table 4). B) Symbols represent plot classifications into seven community types. The circles enclose all sample units associated with a given community.

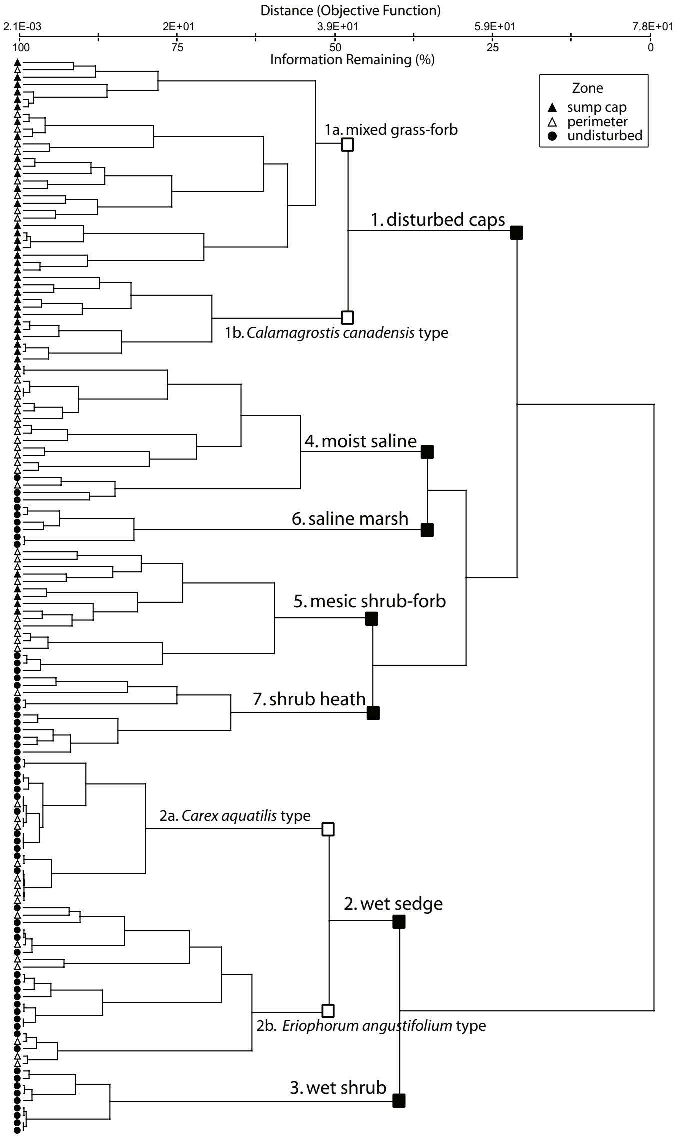

FIG. 7. A classification tree showing hierarchical classification of sample units into seven general community types (indicated by solid squares), with four potential subtypes (indicated by open squares). The scaling of the dendrogram is based on Wishart's objective function and is proportional to the amount of information on plant composition that is retained at different levels of clustering. Plant groups were delimited at approximately the 50% information level, and are labeled on the corresponding branch of the tree.

Examination of the main environmental gradients correlated with the vegetation ordination provides insight into the environmental factors likely to be affecting vegetation composition at the sump sites. The presence of distinct communities on sump caps and their strong association with elevation and moisture gradients supports a general conclusion that decreased moisture availability, in association with cap topography, is the principal reason that the sump cap plant communities are distinct from adjacent, undisturbed tundra (Lawson, 1978; Forbes et al., 2001). Vegetation differences between sumps and surrounding terrain can be expected to persist for as long as the sump covers remain elevated above the surrounding tundra, especially where sumps are situated in poorly drained, alluvial environments.

Vegetation composition of the sump sites was also associated with variations in soil salinity in both disturbed and undisturbed tundra. In undisturbed tundra, salt-

TABLE 3. A list of indicator species associated with community groups identified in the hierarchical cluster analysis.

Community group or subtype	# plots	Indicator species	Indicator value	*p*-value	Observations in group	Total observations	Mean % cover within group
1. Disturbed caps							
1a. Mixed grass-forb	29	*Parnassia palustris*	29.8	0.002	18	25	0.4
		Arctagrostis latifolia	25.6	0.004	19	43	4.3
		Calamagrostis purpurescens	23.5	0.007	7	8	1.8
		Matricaria ambigua	17.2	0.027	5	5	0.3
		Artemisia tilesii	14.2	0.035	9	12	0.5
1b. *C. canadensis* type	12	*Calamagrostis canadensis*	78.7	0.001	11	19	13.5
		Castilleja elegans	48	0.001	7	13	1.8
		Gentiana propinqua	44.6	0.001	7	12	0.4
		Astragalus alpinus	18	0.031	3	6	4.0
		Festuca richardsonii	14.9	0.057	5	21	1.6
2. Wet sedge							
2a. *C. aquatilis* type	20	*Carex aquatilis*	37.9	0.001	20	65	25.0
2b. *E. angustifolium* type	22	*Eriophorum angustifolium*	29.5	0.001	20	58	10.8
		Cardamine pratensis	22.7	0.016	5	5	0.1
		Caltha palustris	18.2	0.013	4	4	0.4
3. Wet shrub	9	*Equisetum variegatum*	78.1	0.001	9	26	12.7
		Eriophorum scheuchzeri	69.6	0.001	9	29	2.4
		Pinguicula vulgaris	41	0.001	4	5	0.3
		Pedicularis sudetica	39	0.002	5	12	0.3
		Salix (height < 30 cm)	35.1	0.003	9	69	6.4
4. Moist saline	19	*Puccinellia borealis*	60.2	0.001	15	18	4.9
		Dupontia fisheri	47.4	0.001	9	9	5.9
		Alopecurus alpinus	30.3	0.003	6	7	1.5
		Ranunculus cymbalaria	26.3	0.005	5	5	0.8
5. Mesic shrub-forb	17	*Equisetum arvense*	73.6	0.001	17	35	10.9
		Salix (height < 100 cm)	27.2	0.01	9	30	13.8
		Primula egaliksensis	23.5	0.012	4	4	0.2
		Cerastium alpinum	17.6	0.012	3	3	0.2
		Epilobium angustifolium	15.7	0.03	3	4	0.9
		Poa glauca	14.3	0.046	3	4	0.4
6. Saline marsh	6	*Ranunculus aquatilis*	100	0.001	6	6	5.0
		Arctophila fulva	94.3	0.001	6	8	10.5
		Hippuris vulgaris	66.7	0.001	4	4	3.0
7. Shrub heath	11	*Vaccinium uliginosum*	72.7	0.001	8	8	5.1
		Dryas integrifolia	71.1	0.001	8	9	3.7
		Carex bigelowii	68.1	0.001	8	11	7.1
		Rubus chamaemorus	63.6	0.001	7	7	3.3
		Cassiope tetragona	63.6	0.001	7	7	1.8
		Arctostaphylos alpina	61.7	0.001	9	19	6.9
		Andromeda polifolia	45.5	0.001	5	5	3.8
		Betula glandulosa	44.7	0.001	5	8	5.1
		Pyrola grandiflora	43.1	0.001	5	6	0.4
		Carex lugens	36.4	0.001	4	4	3.2
		Ledum decumbens	27.3	0.006	3	3	0.4
		Vaccinium vitis-idaea	27.3	0.002	3	3	0.1
		Pedicularis lanata	19.7	0.027	4	11	0.1

tolerant plants were found in lowland areas subject to flooding by brackish water during summer storms, specifically in the area of sump B19. In disturbed areas, salt-tolerant plants were found associated with slopes or depressions on sump caps or perimeters, sometimes adjacent to ponded water. Such localized areas had low total vegetation cover, with patches of bare ground with surficial salt crusts up to several square meters in size. In many sumps, elevated ionic concentrations may be linked to the naturally high salinity of the previously frozen soils used as cap materials, which have been shown to contain elevated levels of soluble Ca^{++} and Mg^{++} (Kokelj and Burn, 2005b).

In general, all of the sumps measured in this study had sufficient plant cover to stabilize the surface of the sump cap and impede soil erosion, but this does not necessarily imply that the sumps have reached a stable physical equilibrium. Several sump caps showed tension cracks in the soil surface, and some had areas of slumping where blocks of soil and vegetation were collapsing into surrounding ponds. Many sumps were surrounded by persistent ponds that formed a partial "moat" around the sump cap, and these areas have remained unvegetated (e.g., the area shown in Fig. 2). Terrain disturbance during construction results in permafrost degradation and is likely to be the original cause of ground subsidence. Cap subsidence can be prolific if the overburden materials are ice-rich or if the portion of the sump containing the majority of liquid wastes begins to thaw. At some sites, the subsided areas appear to have stabilized, but at others, the thermal disturbance caused by the ponds may have contributed to the progressive collapse of the sump cap (Dyke, 2001).

TABLE 4. Correlation coefficients (Kendall's τ) between vegetation ordination axes and environmental variables. Stronger correlations ($\tau > 0.35$) are shown in bold font and included in Figure 7.

Environmental variable	Axis 1	Axis 2	Axis 3
Distance from cap center	**0.409**	-0.077	0.101
Moss cover %	-0.095	**-0.429**	0.051
Bare soil cover %	-0.158	**0.406**	-0.072
Plant litter cover %	-0.086	-0.189	-0.150
Water cover %	**0.370**	-0.081	**0.392**
Organic layer depth	-0.262	-0.338	-0.006
Relative elevation	**-0.532**	0.108	-0.199
Active-layer depth	**-0.394**	0.307	-0.082
Snow depth	-0.073	-0.133	-0.019
Carbon Loss on Ignition (LOI)	0.294	-0.143	0.151
Percent soil saturation	0.264	-0.082	0.115
Conductivity	0.017	0.235	0.103
K (meq/100 g soil)	-0.113	0.215	-0.144
Na (meq/100 g soil)	-0.130	**0.367**	-0.079
Cl (meq/100 g soil)	-0.061	0.328	-0.075

During the winter, winds often remove snow from mounded sump caps, promoting ground cooling and maintenance of frozen ground conditions. Over time, however, growth of tall shrubs can reduce surface wind speeds, increase snow accumulation, and inhibit heat loss (Mackay and MacKay, 1974; Goodrich, 1982; Sturm et al., 2005). In this study, increased depths of snow accumulation were found on sumps vegetated with tall shrubs, but not on those covered primarily with grasses and herbs. This result suggests that variations in vegetation recovery that lead to sumps being covered by shrubs as opposed to grasses may influence winter soil temperatures and the thermal stability of a sump (Hinkel and Kurd, 2006).

The sumps we investigated showed noticeable variation in the area of altered vegetation or soil conditions that was probably due to differences in the nature of the drilling operations or in the sensitivity of different terrain types to disturbance. For example, sump H54 had one of the smallest areas of disturbed vegetation and showed few ponds around the sump perimeter, in contrast to the other sumps in lowland wet sedge tundra. Unlike many of the other sumps, H54 was constructed and abandoned during a single winter season; therefore, materials in the open sump were not exposed to warm summer temperatures. Winter exploration activity may thus have lower ecological impacts than summer activity because operating on an ice pad helps to protect the terrain and vegetation from damage (e.g., Hernandez, 1973).

Vegetation recovery was much more advanced around sump perimeters in lowland wet sedge or wet shrub tundra than at the upland sites. Both sumps constructed in upland shrub-heath tundra had large disturbed areas with frequent bare soil. Upland shrub-heath tundra is dominated by slow-growing shrubs that are very sensitive to physical damage by disturbance (Hernandez, 1973; Forbes et al., 2001; Kemper, 2005). In addition, recovery of shrub-heath species on upland sumps may be limited by the high levels of soil salinity we observed in the perimeter areas of these sumps. Sumps in alluvial terrain are subject to regular flooding, but upland sites experience little leaching from surface runoff, and areas of elevated salinity are likely to persist for decades to centuries (Kokelj et al., 2002). Furthermore, ice-rich permafrost in upland areas may lead to increased levels of ground subsidence associated with disturbance. Other studies from the Mackenzie Delta have noted the higher resilience of lowland, wet graminoid vegetation to disturbance compared to upland, shrub-heath communities (Hernandez, 1973; Kemper, 2005).

CONCLUSIONS

Environmental conditions measured across sumps show differences in elevation and moisture drainage, active-layer depth, snow accumulation, and soil chemical conditions with respect to adjacent undisturbed terrain. These environmental changes are likely to have long-term effects on plant distributions that will outlast the effects of the initial mechanical disturbance caused by sump construction. Even 30 years after disturbance, interactions between topography, plant canopy structure, and snow accumulation can influence sump thermal evolution, with consequences for surface stability and long-term preservation of permafrost conditions in sump caps. Currently, revegetation of the sumps has resulted in the development of total vegetation cover comparable to that observed in undisturbed tundra, but with persistent differences in community composition. Plant communities on these sumps are unlikely to develop a community composition similar to that of surrounding undisturbed tundra as long as topographic differences persist (and in local pockets, until soil chemistry returns to background conditions). Chemical effects of saline soils were most evident in upland sites, where the potential for soil leaching is lower. In lowland sites, plant responses were dominated by physical changes associated with mechanical disturbance, and the smallest disturbance footprints were observed where all exploration activities had taken place over a single winter. Ongoing vegetation recovery and succession on elevated sump caps may eventually result in the formation of small patches of upland tundra, although we found no evidence yet of this. In the more immediate future, revegetated sumps are likely to persist as distinct vegetation communities within the landscape of the Mackenzie Delta region.

ACKNOWLEDGEMENTS

This work has been supported by the Canadian Wildlife Service, Indian and Northern Affairs Canada, the Aurora Research Institute, and the Natural Sciences and Engineering Research Council (NSERC) of Canada through a post-doctoral fellowship and the NSERC Northern Research Chair (CR Burn) at Carleton University. Jonathan Henkelman, Robert Jenkins, Thai Nguyen, Mike Palmer, and Anika Trimble provided valuable assistance with field data collection for this project. We thank Les Kutny, Douglas Esagok, and Denis Chicksi for logistic support in the field. We also thank the three anonymous reviewers whose comments helped improve upon an earlier version of this paper.

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