Delineation of salt contamination in patterned ground

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ABSTRACT
In this study we examined the distribution of salt contamination in hummocky and polygonal permafrost terrain of the Mackenzie Delta region. We hypothesize that contaminant movement in patterned ground is preferentially along trough features. Analysis of soil chloride distribution adjacent to salt-contaminated sumps showed that in polygonal terrain, water-soluble contaminants were more abundant in ice-wedge troughs that were likely enlarged by site disturbance. Sites in hummocky terrain exhibited more uniform chloride concentrations between hummocks and troughs that may be linked to reduced microtopographic differences due to terrain disturbance. In patterned ground, a sampling plan that accounts for surface microtopography will likely better delineate salt contaminants.

RÉSUMÉ
Dans cette étude nous avons examiné la distribution de contamination de terrain charactérisé par une abondance de hummocks et polygons de pergélisol de la région du delta de Mackenzie. Nous présumons que le mouvement de contaminant en terre modelée est préférentiellement le long des dépressions. L'analyse de la distribution de chlorure de sol à côté des bassins à boues de forage a prouvé que dans le terrain polygonal, les contaminants hydrosolubles étaient plus abondants dans les dépressions glace-coincent qui ont probablement été agrandis par perturbation d'emplacement. Les emplacements dans le terrain charactérisé par une abondance de hummocks ont montrés des concentrations plus uniformes en chlorure entre les hummocks et les dépressions qui peuvent être liés aux différences microtopographic que réduites dues à la perturbation du terrain. En terre modelée, un plan de prélèvement explique la surface microtopographic extérieur tracera probablement mieux des contaminants.

1 BACKGROUND AND OBJECTIVES

Patterned ground is ubiquitous in the Canadian arctic and refers to the systematic arrangement of microrelief that is usually the result of freezing and thawing soil (Williams and Smith 1989). Patterned ground includes plot-scale landforms that are formed by cryoturbation, such as earth hummocks and high center ice-wedge polygons (Williams and Smith 1989, van Everdingen 2005). Both landforms result in site microtopography characterized by elevated land surfaces (Eg. hummock or polygon center) surrounded by a network of inter-connected troughs that concentrate drainage and influence water movement (Lawson 1986, Quinton and Marsh 1998). Patterned ground is also associated with small-scale variations in soil texture between trough and inter-trough features that affects their permeability and influences subsurface drainage (Quinton and Marsh 1998, Barnes and Filler 2003). In the thaw season, water movement occurs preferentially through the slightly depressed, highly permeable, saturated layer of the interconnected trough features (Lawson 1986, Quinton and Marsh 1988). For instance, in hummocky terrain, relatively impermeable, clay-rich hummocks deflect water flow into interconnected, organic-rich troughs and in some cases water may flow perpendicular to the topographic gradient.

Water-soluble contaminants associated with spills are often highly soluble and easily transported by water through the soil, so that mechanisms controlling water movement also control contaminant movement (Alberta Environment 2001). Soil sampling strategies to delineate contaminants are often based on coarse-scale topography (Lund and Young 2005); but, this strategy may be less effective in patterned ground because it does not account for preferential water flow associated with surface microtopography and variation in soil characteristics between trough and inter-trough features. We hypothesize that in patterned ground, specifically high-center polygons and earth hummocks, water-soluble contaminants move preferentially through troughs.

In northern Canada, salt contamination has been associated with seepage from drilling-mud sumps (Dyke 2001). Briny circulating fluids used in exploratory hydrocarbon drilling are often encapsulated in sumps that are designed to remain frozen, but several studies have noted unfrozen conditions and the movement of drilling-muds away from the sump through the active layer (Dyke 2001, Jenkins et al. 2008, Kokelj et al. 2010). We used saline seepage from drilling-mud sumps as a tracer to study contaminant movement in patterned ground. The objectives of this paper are to 1) evaluate the vertical and lateral distribution of salts in patterned permafrost terrain, 2) compare and explain differences in the distribution of salts in hummocky and polygonal landforms. The goal of this research is to contribute to guidelines to delineate water-soluble contaminants in patterned ground.

2 METHODS

A draft soil sampling protocol to delineate water-soluble contaminants in patterned ground was developed based on a literature review of cryosol structure and field conditions (Zajdlik et al. 2008). The protocol was tested adjacent to six drilling-mud sumps in patterned terrain that exhibited a salt contaminant pathway leading from the sump, as identified by electromagnetic (EM-38) surveys (Figure 1) (Komex International & IEG Environmental 2005). Three sites were in hummocky terrain and three in polygonal. Soil sampling was conducted in August 2008, and July and August 2009. Samples in undisturbed terrain could not be obtained at several control transects in July 2009 because the ground remained frozen. All sites were located in Quaternary tills of the tundra uplands adjacent to the Mackenzie Delta, Northwest Territories.

Transects were established along the contaminant pathways at increasing distances from the sump to assess the effect of linear distance from the contaminant source on salt concentrations. At each site, three transects were established across pedons located at increasing distances from the contaminant source (Figure 2). A fourth transect was located in nearby undisturbed terrain as a control. Each transect traversed a pedon, the basic unit of soil structure (Tarnocai 2004). Transects extended from the middle of the inter-trough feature to the middle of the trough (Figure 3). Soil samples were collected at three evenly-spaced locations in the inter-trough feature and three in the trough. At each point, soil samples were collected with an 8-cm diameter, 1-m long soil auger at three depths in mineral soil representing the top, middle, and bottom of the active layer. Relative active-layer depths were used because absolute active-layer depths varied widely between contaminated and control transects. Terrain disturbance, such as sump construction, can lead to deepening of the active layer in comparison to undisturbed terrain (Mackay 1995). The

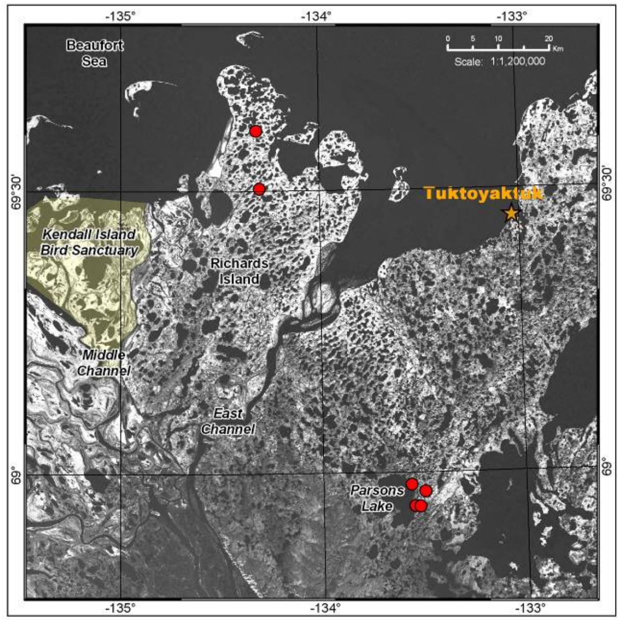


Figure 1 Study sites at 6 drilling-mud sumps in the outer Mackenzie Delta.

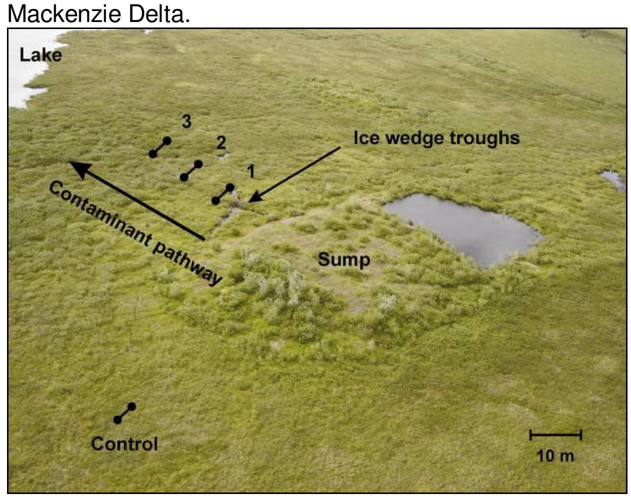


Figure 2 Configuration of soil sampling transects at a sump in polygonal terrain. Transects 1 to 3 are located along the contaminant pathway at increasing distances from the sump. The control transect is located in undisturbed terrain. Note the enlargement of ice-wedge troughs along the contaminant pathway.

surface organic layer was not sampled to limit the study to mineral soils. Physical features were also measured to characterize the sites, including active-layer depth using a metal probe, relative surface elevation with a Trimble-R3 differential GPS, surface organic-layer thickness and patterned-ground microtopography.

Chloride was used as an indicator of salinity because it is a constituent of drilling muds, but background concentrations in uplands of the Mackenzie Delta region are relatively low (Dyke 2001, Kokelj and Burn 2005). Soil samples were analyzed at a laboratory for chlorides with a detection limit of 0.06 meq/L (McKeague 1978). Soil samples from corresponding trough and inter-trough features at 19 transects were analyzed for soil texture (Carter 1993).

The data for chloride concentrations from each site were visually inspected using box and whisker plots and described with summary statistics. Statistical differences between site physical conditions were analyzed with the non-parametric Mann-Whitney U test at the 0.05 significance level. Nested mixed effects models were used to test for statistically significant differences in chloride concentrations between sites, transects, trough and inter-trough features, and soil layers. Patterned-ground microtopography and soil layer were treated as fixed effects, transects were treated as random effects and heterogeneity of variance among sites was modelled explicitly.

3 RESULTS

3.1 Site Conditions

Physical characteristics of the contaminated and control transects were compared for each terrain type (Tables 1 and 2). Soil texture at the sites varied from a silt loam to a clay loam, but there were no categorical differences

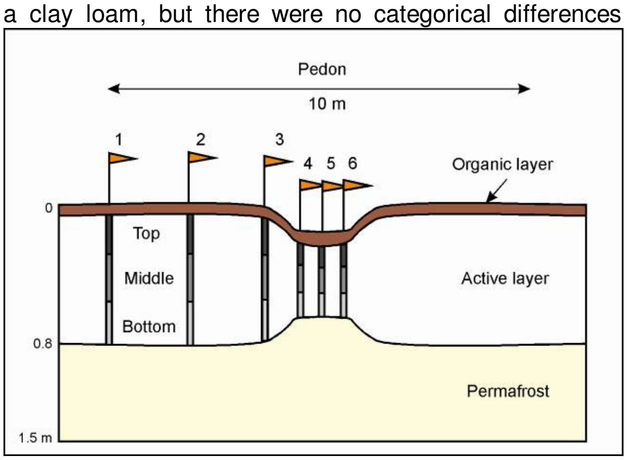


Figure 3 A typical soil sampling transect in patterned ground with sample points at three locations in the trough and three in the inter-trough feature marked by flags. Samples were taken at the top, middle and bottom of the active layer at each point.

between mineral soils of trough and inter-trough features in either hummocky or polygonal terrain. At control transects in hummocky terrain, troughs were characterized by significantly thicker organic layers and active layers were significantly thinner than those of the hummocks (Table 1). There were no corresponding differences between hummocks and troughs at transects along the contaminant pathway. In polygonal terrain, there were no significant differences in active-layer depth or organic-layer thickness between polygon centers and ice-wedge troughs at control or contaminated transects. A comparison of contaminated and control transects in both hummocky and polygonal terrain found that active layers were significantly deeper and organic layers were significantly thinner on the contaminated transects.

Patterned-ground microtopography was compared between control and contaminated transects to assess changes associated with disturbance (Table 2). In polygonal terrain, troughs in the contaminant pathway were considerably deeper (15 to 28 cm) than those of the control transects. Two of the three polygonal sites had noticeably wider troughs (15 to 54 cm) in the contaminant pathway than in undisturbed terrain. Differences between contaminated and control transects at hummocky sites were much less pronounced than at polygonal sites, with smaller differences in control trough elevations (2 to 7 cm) and trough widths (1 to 24 cm).

3.2 Soil Chemistry

Chloride concentrations at transects along the contaminant pathways were elevated relative to the control transects at all of the study sites (Figure 4). Only one site (Ivik N-17) exhibited a linear decrease of median chloride concentrations in the troughs with distance from the sump. At the remaining sites, there was either no discernable gradient or chlorides increased with distance from the sump.

At polygonal sites, median chloride concentrations were consistently elevated in the troughs at all depths along transects in the contaminant pathway (Figure 4).

Table 1 Comparison of median active-layer depths and organic-layer thicknesses between A) contaminated and control transects and B) trough and inter-trough features. Significant differences are boxed, and C) corresponding Mann-Whitney U and p-values are reported.

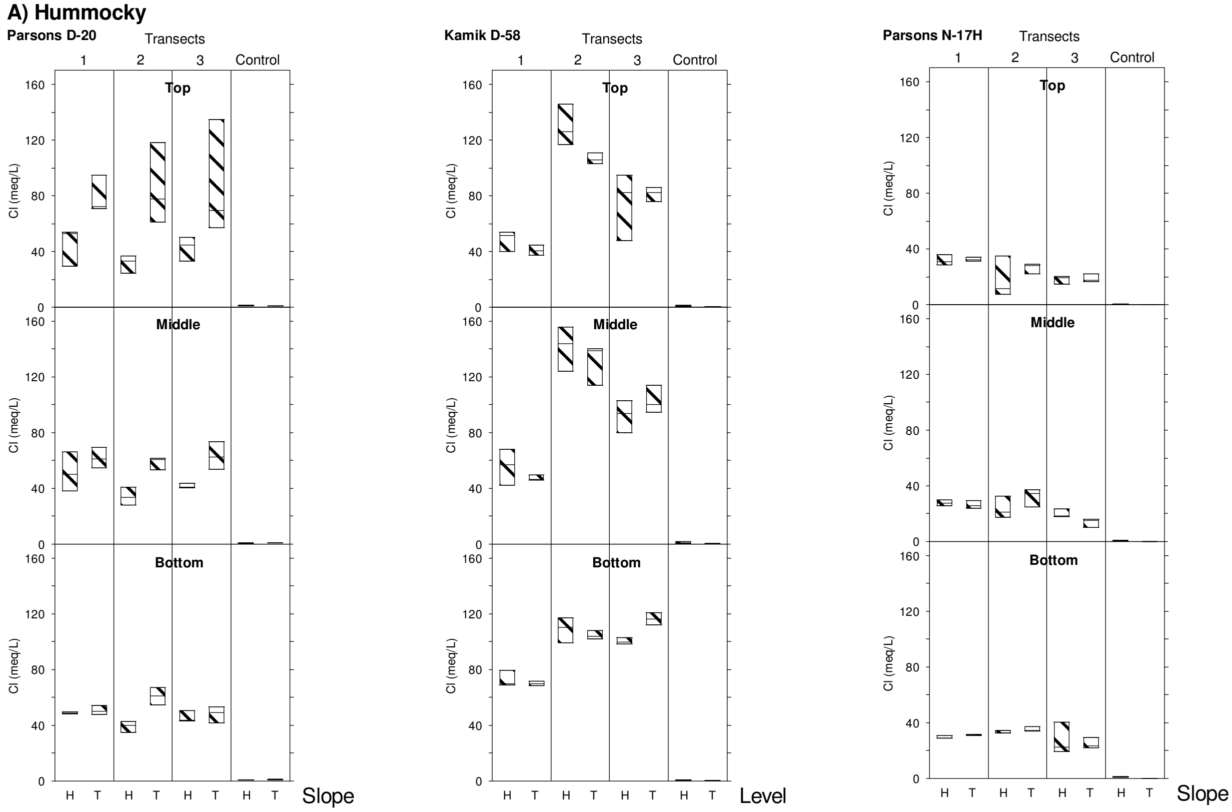
A)		Hummocky		Polygonal	
Active layer (cm)	Contaminated (n=54)	67[1]		64[2]	
	Control (n=18)	49		39.5	
Organic layer (cm)	Contaminated (n=54)	6.5[3]		1.5[4]	
	Control (n=18)	13.5		6.5	
B)		Hummock/ Trough		Polygon/ Trough	
Active layer (cm)	Contaminated (n=27)	70	64	65	64
	Control (n=9)	**55**[5]	**19**	40	37
Organic layer (cm)	Contaminated (n=27)	5	9	1	2
	Control (n=9)	**10**[6]	**18**	5	8

C)	1	2	3	4	5	6
U-value	253	102	233	166	12.5	7.5
p-value	0.002	0.001	0.001	0.001	0.015	0.004

Table 2 Comparison of trough widths and elevation differences between troughs and inter-trough features at transects in the contaminant pathway and control transects at hummocky and polygonal sites. Trough widths were measured at the widest contaminated transect and the control transect. The elevation difference is the distance from the top of the inter-trough feature to the bottom of the trough.

Transects	Trough width (cm)	Elevation difference (cm)
A) Hummocky		
	Parsons D-20	
Contaminated	70	27
Control	65	24
	Kamik D-58	
Contaminated	38	25
Control	39	23
	ParsonsN-17H	
Contaminated	70	23
Control	46	30
B) Polygonal		
	Ivik N-17	
Contaminated	80	50
Control	80	22
	Umiak N-10	
Contaminated	32	53
Control	17	38
	Parsons N-17P	
Contaminated	85	41
Control	31	18

A) Hummocky



B) Polygonal

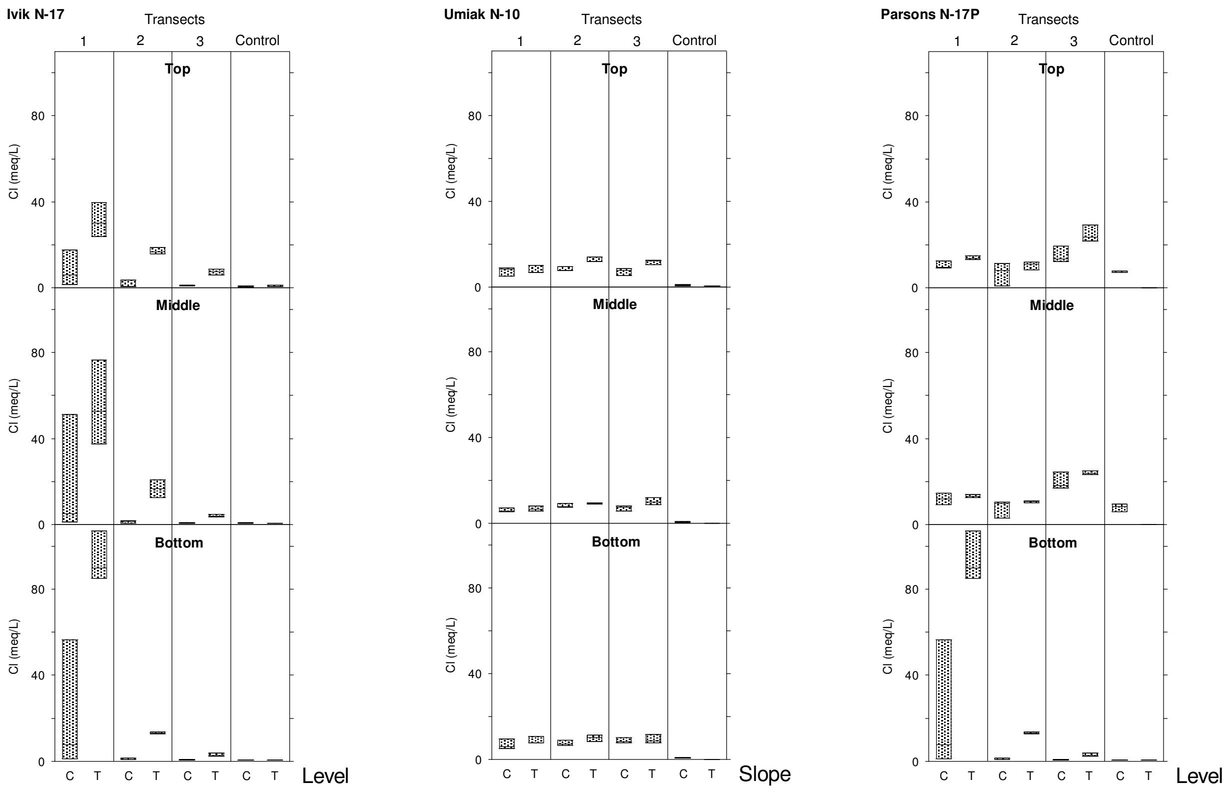


Figure 4 Box and whisker plots of chloride concentrations at hummocky and polygonal sites. Note the y-axis scale is variable. Abbreviations include: H: hummock, T: trough, C: polygon center. Slope and level refer to site topography.

The variation of median chloride concentrations between trough and inter-trough features was much greater than the differences between transects. This pattern was repeated at most of the transects in hummocky terrain; however, at two sites (Kamik D-58, Parsons N-17H), median chloride concentrations at several transects were either equal or slightly elevated in the hummock tops relative to the troughs. There were no demonstrable patterns of vertical distribution of chlorides in the soil profile in polygonal or hummocky terrain.

Separate nested mixed effects models were used to determine if there were significant differences in chloride concentrations between trough and inter-trough features, and active-layer depths in hummocky and polygonal terrain. The polygonal model showed that the differences in chloride concentrations between ice-wedge troughs and polygon centers were statistically significant ($V=0.295$, $p=0.001$), but there were no significant differences in chlorides between relative soil depths. The model for hummocky sites did not distinguish significant differences in chloride concentrations between trough and inter-trough features or soil depths, so separate models were applied to each site. A significant difference of chlorides between hummocks and troughs was found at one site (Parsons D-20) ($V=0.332$, $p=0.070$).

4 DISCUSSION

Patterned ground complicates drainage and contaminant movement in permafrost terrain. Based solely on topography, one would expect chloride concentrations to decrease with distance from a contaminant source, but soil sampling nearby six drilling-mud sumps with evidence of external salt contamination found that chloride levels were unrelated to linear distance from the contaminant source at most sites.

In polygonal terrain, higher levels of chlorides were measured in the troughs at all depths relative to the polygon centers (Figure 4), and a multivariable model indicated a statistically significant difference between chlorides in the troughs and polygon centers. These results imply the preferential movement of water-soluble contaminants through the troughs in polygonal terrain. Drainage and contaminant movement may become more concentrated within ice-wedge troughs in disturbed terrain because surface disturbance causes thawing of the ice wedge and trough enlargement (Table 2). The deepening and widening of ice-wedge troughs in response to physical disturbance is corroborated by observations of 30-year old exploratory drilling sites in polygonal terrain of Alaska (Lawson 1986). Shallow (<1-m), wide (>30 m) topographic depressions have been observed surrounding many sumps in the delta region (Johnstone & Kokelj 2008, Kokelj et al. 2010) and are likely related to ice wedge thaw in polygonal terrain. These depressions may store pockets of contaminants nearby the sump cap.

In contrast with ice-wedge sites, differences in chloride concentrations between hummocks and troughs were only significant at one site (Figure 4). Contaminant distribution may have been similar in the hummocks and troughs at the remaining sites because of hummock degradation due to terrain disturbance (Figure 5). Disturbance in hummocky terrain has been related to thaw subsidence and hummock collapse resulting in decreased hummock relief and trough widths (Table 2) (Kokelj et al. 2007). Differences between active-layer and organic-layer depths of hummocks and troughs were reduced on contaminated transects with respect to undisturbed sites (Table 1). Reduced microtopographic differences between hummocks and troughs at extensively disturbed sites may lead to drainage and contaminant movement that is similar to non-patterned ground.

Systematic differences in chloride concentrations between the top, middle and bottom of the soil column were not observed, but we hypothesize that topography and soil moisture conditions likely contribute to the vertical patterns of salt distribution at the study sites. Of the three sites located on a slope, two had higher concentrations of chlorides in the top layer of mineral soil, and two of the three sites located on level ground had more chlorides concentrated in the middle and bottom layers (Figure 4). Over a year, soils at well-drained permafrost sites on a slope may be drier, drawing pore water and salts to the surface through evaporation, while poorly-drained soils on level ground remain wetter allowing salts to stay closer to the base of the active layer (Kokelj and Burn 2005). We recommend that future research compare soil moisture throughout the thaw season along with soil chemistry at sloping and level patterned-ground sites.

This research indicates that in permafrost terrain, soil sampling strategies to delineate -water-soluble contaminants should account for patterned-ground features in addition to coarse-scale factors such as topography. In polygonal terrain, greater sampling effort should be focused on ice-wedge troughs, whereas sampling at hummocky sites, particularly those with extensive hummock degradation, should include a balance of hummocks and troughs. It is likely that at sites where hummocks are not degraded, contaminants will be concentrated along drainage pathways in the troughs, but further research is required to confirm this.

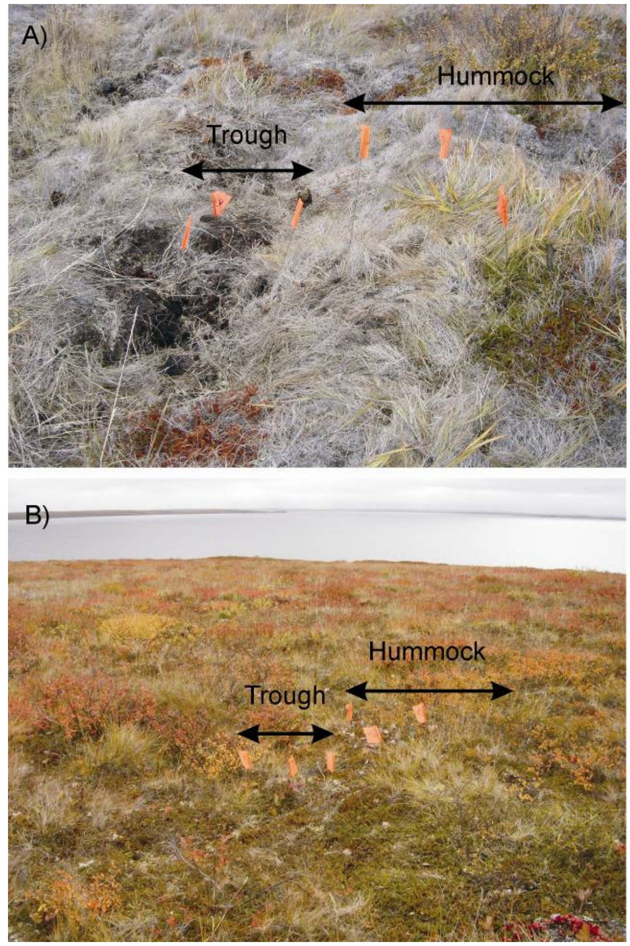


Figure 5 Soil sampling transects marked by flags in hummocky terrain. The transect in A) is affected by extensive salt contamination evidenced by the chlorotic vegetation and hummock degradation; and B) is a control transect in undisturbed terrain with intact hummocks and healthy vegetation.

5 CONCLUSIONS

Based on the analysis of site conditions and soil chemistry, the following conclusions can be made: 1) The effects of patterned-ground features should be considered when designing soil sampling programs or interpreting data from terrain in patterned ground; 2) In polygonal terrain, water-soluble contaminants are concentrated in ice-wedge troughs that may have become wider and deeper in response to terrain disturbance; 3) At hummocky sites, where terrain has been disturbed, reduced microtopography between hummocks and troughs contributes to fairly uniform contaminant concentrations across a pedon; 4) In patterned ground, for a fixed sampling effort, a sampling plan that accounts for terrain features and soil depth will likely better delineate salt contaminants than a random sampling design, or one that only accounts for site topography.

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