Permafrost, Phillips, Springman & Arenson (eds)
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'Drunken forest' and near-surface ground ice in Mackenzie Delta, Northwest Territories, Canada

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ABSTRACT: In Mackenzie River delta, emergent point bars are colonized by straight white spruce trees in association with alder and willow bushes. On older surfaces, colonized by mosses, the trees are characteristically leaning. In white spruce communities above the level of regular flooding, the trees are stunted and tilted. Tree lean and ground ice content were measured at 18 sites in the delta. There is a clear, positive association between the ice content of near-surface permafrost in drill core samples and the extent of tree lean at the sites. The relation between near-surface ground ice and tree lean suggests that aggradation and/or degradation of ice-rich permafrost can result in the tilting of spruce trees, and that forest structure may be used to predict near-surface ground ice content in Mackenzie Delta.

1 INTRODUCTION

Subarctic "drunken" forests underlain by permafrost are characterized by randomly leaning spruce trees (Zoltai 1975). On hummocky terrain, annual heave and settlement of the active layer can shift trees, causing them to lean (Zoltai and Tarnocai 1974). However, in even-aged stands of fire origin, tilting is initiated when trees are between 50 and 100 years old (Zoltai 1975). This observation suggests that aggradational ice development associated with post-fire active-layer thinning causes the overlying ground to heave and the trees to tilt (Zoltai 1975).

The objective of this paper is to describe the relations between spruce forest structure and near-surface ground ice characteristics in Mackenzie River delta, Northwest Territories. Active-layer characteristics and the configuration of the permafrost table were measured at an actively aggrading site with straight growing white spruce and at a site elevated above the level of regular flooding with stunted, tilted trees (Fig. 1). Data on ground ice and spruce forest characteristics were obtained from these two sites and from 16 other sites throughout eastern Mackenzie Delta. These investigations are of practical utility, because the identification of thaw-sensitive terrain in the delta region is required to plan the development, and manage the impacts, of renewed hydrocarbon exploration and future gas production.

2 FOREST COMMUNITIES IN EASTERN MACKENZIE DELTA

The Mackenzie Delta, is approximately 150 km long and 60 km wide (Fig. 1). The Delta is characterized by an intricate network of migrating channels and numerous lakes (Mackay 1963). Permafrost is generally less than 100 m thick due to the thermal effect of water bodies and the shifting nature of the channels (Smith 1976). Ground ice investigations near Aklavik indicate that segregated ice is concentrated in the upper 2 to 3 m of alluvial sediments (Philainen and Johnston 1954). Ice-wedge polygons are present on elevated surfaces throughout the Delta but sedimentation and organic accumulation obscure their surface expression (Mackay 1963).

In Mackenzie Delta, spruce/alder-bearberry (*Picea/Alnus-Arctostaphylos*) communities colonize regularly-flooded surfaces of the delta plain (Pearce *et al*. 1988). The sandy silt alluvium forms static cryosolic soils in which an active layer 80–100 cm deep develops. Spruce trees grow vigorous and straight, and survive sedimentation and aggradation of permafrost with the assistance of adventitious roots (Gill 1975).

Spruce/feathermoss (*Picea/Hylocomium*) forests replace the spruce/alder-bearberry communities in association with surface aggradation and a decline in flood frequency and sedimentation rate (Pearce *et al*. 1988). Development of a moss cover modifies the ground thermal regime causing the active layer to become shallower (Smith 1975). Although the roots of many older spruce trees are anchored in permafrost, most trees lean. The soils are organic cryosols and the alluvium is silty loam. Maximum thaw depths at these sites range from 50 to 70 cm.

Spruce/crowberry-lichen (*Picea/Empetrum-Cladina*) woodlands occupy surfaces elevated above the level of regular flooding (Pearce *et al*. 1988). The spruce trees are stunted and leaning with no consistency in the direction of tilt. Such forests with trees ranging in age from 250 to 475 years are underlain by a thin active layer consisting of clayey silts overlain by a thick layer of organic material. Turf hummocks characterize surface microtopography and maximum

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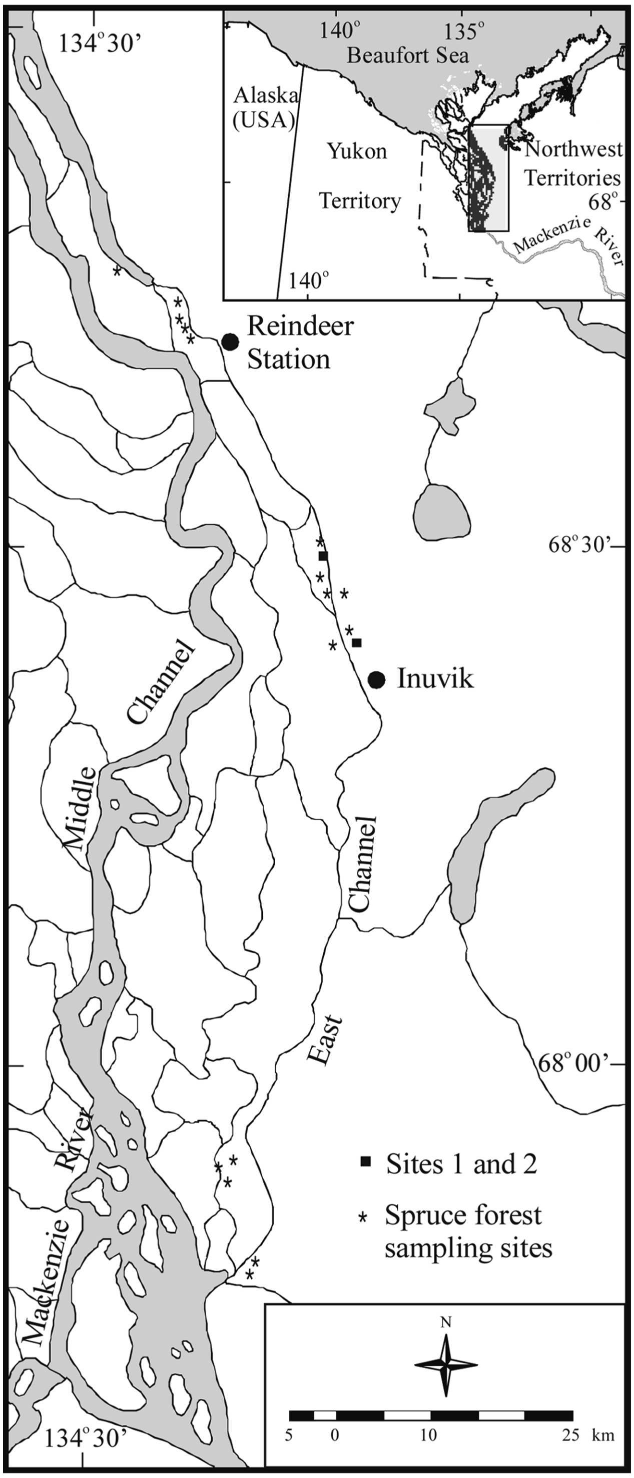

Figure 1. Eastern Mackenzie Delta and study sites. Boxes indicate Site 1 and 2; stars indicate the additional sampling sites.

thaw depths range between 30 and 70 cm (Gill 1973). Many of the old trees are anchored in permafrost.

3 FIELD AND LABORATORY METHODS

To contrast the physical characteristics of the permafrost table between aggrading and inactive Delta surfaces, active-layer depths and permafrost-table microtopography were evaluated at 1 m intervals along 30 m transects at two sites, one in a spruce/alder-bearberry community (Site 1) and the other in a spruce/crowberry-lichen community (Site 2). Depth to thaw was determined using a steel probe pushed down to refusal. Unfrozen moisture content characteristic curves for the silty alluvium, determined by TDR at Carleton University, indicated that less than 10% of soil water remained unfrozen at temperatures below −0.7°C. Consequently, the depth of refusal corresponded well with the 0°C isotherm. At each site, active layer sampling points were leveled with respect to a benchmark so that permafrost table relief could be determined. The benchmark was referenced to the water level in adjacent East Channel. Using daily water level data for East Channel at Inuvik, the elevation of the benchmark was tied into the geodetic marker at Inuvik (Water Survey of Canada data), enabling the elevations to be reported with respect to sea level.

From 1999 to 2001, shallow permafrost cores were obtained from a total of 18 spruce forest sites throughout eastern Mackenzie Delta. Cores were extracted from the active layer and near-surface permafrost using a two-inch diameter CRREL core barrel to depths of 1.5 m. The core samples were sectioned in 10 cm intervals, logged, double bagged, and returned to a laboratory in Inuvik. The permafrost samples were thawed and homogenized, poured into pre-weighed beakers and allowed to settle. The samples were weighed and the volumes of sediment and supernatant water were recorded so that excess ice content of the samples could be estimated using:

$$\text{Excess ice (\%)} = [(W * 1.09)/(S + (W * 1.09))] * 100 \tag{1}$$

where W is the volume of supernatant water (cm^3), multiplied by 1.09 to estimate the equivalent volume of ice, and S is the volume of saturated sediment (cm^3).

The samples were dried for 24 hours at 105°C and weighed in order to determine field moisture content. Forest characteristics including tree tilt, orientation of lean, diameter at breast height and tree height were recorded for six to ten white spruce trees at each of the 18 core locations.

4 RESULTS

4.1 *Permafrost table and ground ice characteristics*

Homogeneous active-layer depths and minimal surface microtopography at Site 1 indicated a planar permafrost table beneath the spruce/alder-bearberry community (Fig. 2). The near-surface permafrost was ice-poor, with

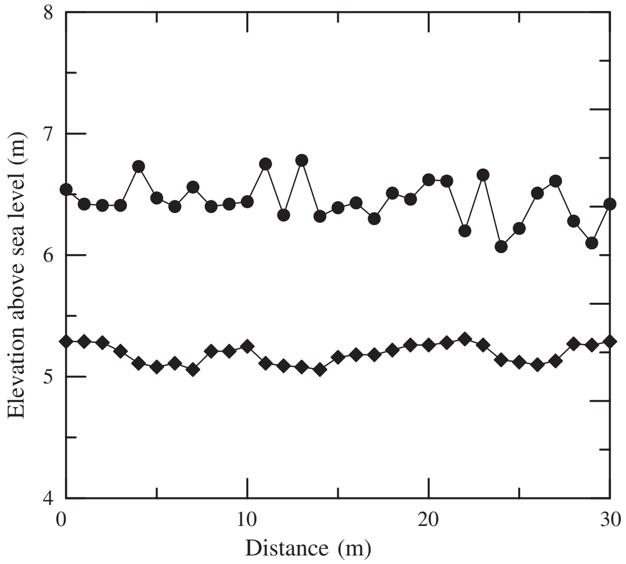

Figure 2. Permafrost table relief, 30 m transects, Site 1, spruce/bearberry-lichen community (◆), and Site 3, spruce/crowberry-lichen community (●), August 2001, Mackenzie Delta.

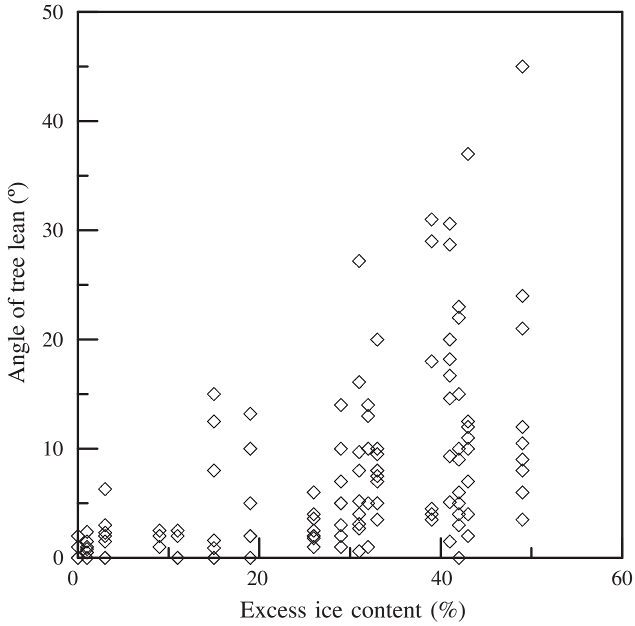

Figure 3. Excess ice content in the top 50 cm of permafrost and angle of tree lean for 6 to 10 spruce trees at permafrost sampling sites, eastern Mackenzie Delta.

an excess ice content of between 0 and 10%. At Site 2, mean depth of thaw was 50 cm and the permafrost table was irregular (Fig. 2). At Site 2, the mean difference in permafrost table relief at 1 m intervals was 21 cm in contrast to only 4 cm at Site 1. The permafrost at Site 2 was ice-rich, with excess ice content between 35 and 45% by volume.

4.2 *Ground ice and forest characteristics throughout eastern Mackenzie Delta*

Figure 3 displays data gathered at 18 sites in Mackenzie Delta, and indicates that spruce forests with tilted trees are underlain by ice-rich permafrost. At sites where the ice content of near-surface permafrost was greater than 40%, all trees were tilted, some by more than 25°. At sites underlain by medium ice content (10–35% excess ice), most trees were leaning, but maximum tilt was generally not as great as at high ice content sites. Spruce forests with straight trees were underlain by ice-poor permafrost with excess ice contents below 15%.

Figure 4 indicates the mean tree tilt of six to ten spruce trees surrounding each permafrost core site and the near-surface excess ice content of the ground at each site. Forest community type was used to group these data. Spruce/alder-bearberry forests consisted of straight trees underlain by ice-poor permafrost. The mean tree lean in spruce/feathermoss forests ranged from 3 to 12° and ice content of near-surface permafrost was medium to high. The mean tilt of trees in spruce/crowberry-lichen woodlands was greater than 10° and near-surface permafrost was ice-rich.

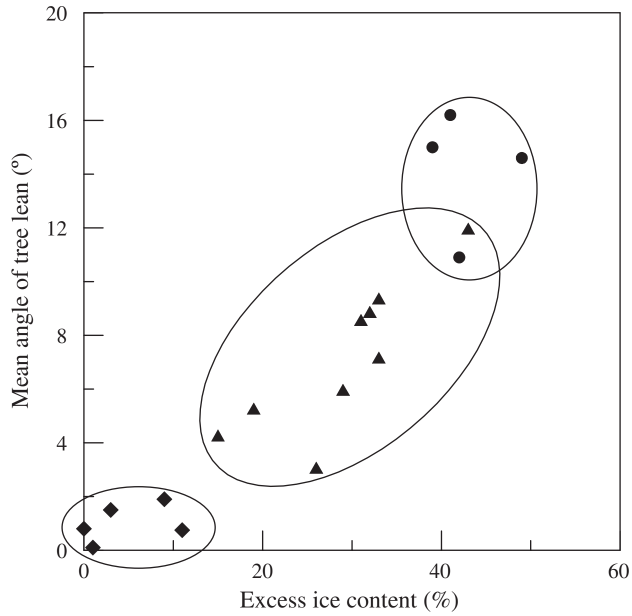

Figure 4. Relation between excess ice content in the top 50 cm of permafrost and mean angle of tree lean at 18 sites in eastern Mackenzie Delta. Forest type was used to group these data: Spruce/alder-bearberry (◆), spruce/feathermoss (▲) and spruce/crowberry-lichen (●).

The mean excess ice content in near-surface permafrost for spruce/alder-bearberry sites was 5%. Ice content in the top 50 cm of permafrost at spruce/feathermoss forests ranged from 15 to 43% and the mean of nine sites was 29%. The mean excess ice content in permafrost beneath spruce/crowberry-lichen woodlands was 43%. Analyses of variance indicated that the mean ice content was significantly different

($P < 0.01$) between the three respective forest communities.

5 DISCUSSION

An ice-rich zone in near-surface permafrost can develop where an aggrading permafrost table traps ice lenses that have formed at the base of the active layer during two-sided freeze-back (Mackay 1972). Also, during the summer, moisture is drawn downward along a thermally-induced suction gradient from the active layer into permafrost (Cheng 1983; Mackay 1983). The annual downward flux may be greater than water movement out of this zone in winter, when the temperature gradient is reversed because of the large seasonal difference in hydraulic conductivity of near-surface permafrost soils (Cheng 1983). Over time, a small annual accumulation of moisture may lead to development of an ice-rich zone.

The growth of this ice-rich zone may contribute to the tilting of spruce trees in Mackenzie Delta. On frequently flooded surfaces, such as point bar willow and spruce/alder-bearberry communities, rapid aggradation of the permafrost table and the low frost-susceptibility of sandy silts inhibit ice enrichment in permafrost. As these surfaces aggrade, flood frequency decreases and finer alluvium is deposited. Ice accumulation then occurs in near-surface permafrost because frost-susceptible sediments and gradual aggradation of permafrost favour ice enrichment (Shur and Jorgenson 1998).

In the Delta, long-lived spruce trees survive aggradation of the permafrost table and development of near-surface ground ice. Uneven aggradation of the permafrost table is illustrated by the transition from a planar frost table beneath aggrading surfaces, to an undulating frost table beneath older, elevated Delta surfaces (Fig. 2). Differential aggradation of permafrost and variability in ground ice development can enhance surface micro-relief and contribute to the gradual tilting of trees anchored in permafrost. Where ice-rich sediments underlie spruce forests, degradation of permafrost resulting from disturbance or extreme thaw events can cause differential subsidence and tree tilting. In contrast, degradation of ice-poor permafrost would not effect tree lean because thaw-settlement would be minimal.

The effect of aggradational ice development or subsequent thaw-subsidence on tree lean is suggested by data in Figure 3 which show that forests with straight trees are underlain by ice-poor permafrost and forests with tilted trees are underlain by ice-rich permafrost. Excess ice content plotted against mean site tree tilt illustrates that forest type can be used to predict near-surface ground ice characteristics (Fig. 4). The relation in Figure 4 is useful in determining thaw-sensitive terrain in Mackenzie Delta because forest communities can be mapped using various remote-sensing techniques.

6 CONCLUSIONS

From these results the following conclusions are drawn:

1. In Mackenzie Delta, forests with tilted trees were underlain by permafrost of high ice content and forests with straight trees were underlain by ice-poor permafrost. This relation suggests that the aggradation and/or degradation of ice-rich permafrost contribute to the tilting of spruce trees in Mackenzie Delta.
2. Spruce forest type may be used to predict the near-surface ground ice characteristics in Mackenzie Delta.

ACKNOWLEDGEMENTS

This work has been supported by NSERC, the Northern Science Training Program, Indian Affairs and Northern Development Canada, the Aurora Research Institute, and the Polar Continental Shelf Project, Natural Resources Canada. Assistance from Douglas Esagok and from Les Kutny is gratefully acknowledged. Facilities at the Taiga Environmental Laboratory, Yellowknife, were provided by Bill Coedy, Indian Affairs and Northern Development Canada, Anne Wilson, Environment Canada, and Brett Elkin, Government of the Northwest Territories. Wade Hanna and Randy Wedel, Water Survey Division, Environment Canada, provided the hydrometric data. Office support was provided to SVK by Hal Mills, Geonorth Ltd. Phil Wilson drafted Figure 1. Shawne Kokelj provided helpful comments on the manuscript. PCSP Contribution No. 02302.

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