Influence of White Spruce Trees on Permafrost-Table Microtopography, Mackenzie River Delta[1]

DON GILL

Boreal Institute for Northern Studies, The University of Alberta, Edmonton, Alberta T6G 2E9

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The topography of the permafrost table in the Mackenzie River Delta is remarkably uniform. However, differences in active layer thickness are characteristically found around the stems of white spruce trees where conical depressions occur in the permafrost table. The locally increased active layer thickness appears to result from the interaction of the following factors, all of which cause greater heat diffusivity into the soil near tree stems: (1) some 25% of the gross rainfall is intercepted by individual spruce crowns, which causes a corresponding decrease in soil moisture below the tree; (2) accelerated sediment deposition around spruce stems during the spring flood creates small alluvial deposits that provide a locally better drained site; (3) the growth of insulative mosses around tree stems is also retarded by the increased sediment deposition; and (4) the low-albedo slopes of alluvial deposits surrounding tree stems intercept more solar radiation than the normal flat surfaces away from trees.

La topographie de la table de permafrost dans le delta du McKenzie est remarquablement uniforme. Cependant des différences d'épaisseur dans les couches actives sont toujours localisées aux pieds des sapins blancs où l'on retrouve une dépression conique dans la table du permafrost.

Ces différences d'épaisseur semblent être le résultat d'une interaction des facteurs suivant, qui tous cause un transfert de chaleur dans sol, près du pied de l'arbre: environ 25% de la pluie tombant sur la surface de l'arbre est interceptée par l'arbre lui-même ce qui cause une diminution de l'humidité sous les arbres; un dépôt plus important de sédiment autour du pied de l'arbre pendant les crues de primptemps produit une petite quantité de dépôt alluviaux occassionnent un meilleur drainage locale; la croissance de mousse isolante autour du pied est retardée par cette augmentation de sédimentation; ces dépôts alluviaux ayant une pente de faible albedo interceptent plus de radiations solaires que les surfaces plates éloignées des arbres.

[Traduit par le journal]

Introduction

In areas that are underlain by permafrost, variations in the topography of the permafrost table are often related to the distribution of vegetation (Benninghoff 1952; Brown 1966; Brown and Péwé 1973; Tyrtikov 1973). Unevenly distributed vegetation and the resultant accumulations of organic material cause differences in the ground moisture and thermal regimes, with the result that where vegetation is concentrated, the active layer is normally thinner. In areas of discontinuous permafrost, even individual white spruce (*Picea glauca*) trees may influence the ground moisture and thermal regimes to the extent that lenses of permafrost may form beneath them (Viereck 1965; Gill and Jacobson 1973). In contrast to Viereck's findings in Alaska, and Gill and Jacobson's similar findings in the Kluane Lake area of the Yukon Territory, the present study illustrates that in the Mackenzie River Delta, the permafrost table beneath white spruce trees is normally depressed in a conical shape surrounding the stem.

The Study Area

Figure 1 indicates the study location (shown as "Intensive study area" on map) within the modern Mackenzie River Delta. The physical geography of the delta region, including the climate, has been described in detail by Mackay (1963); climate of the delta has also been described by Abrahamsson (1966), Gill (1971), and Burns (1973). The coastal portion of the Mackenzie Delta lies within the Arctic climatic zone and its southern portion is in the Subarctic; the study site is transitional between the two. Mean daily temperatures at Inuvik, 48 km southeast of the study site, range from −30 °C in January to 13.5 °C in July. Precipitation is low; rainfall

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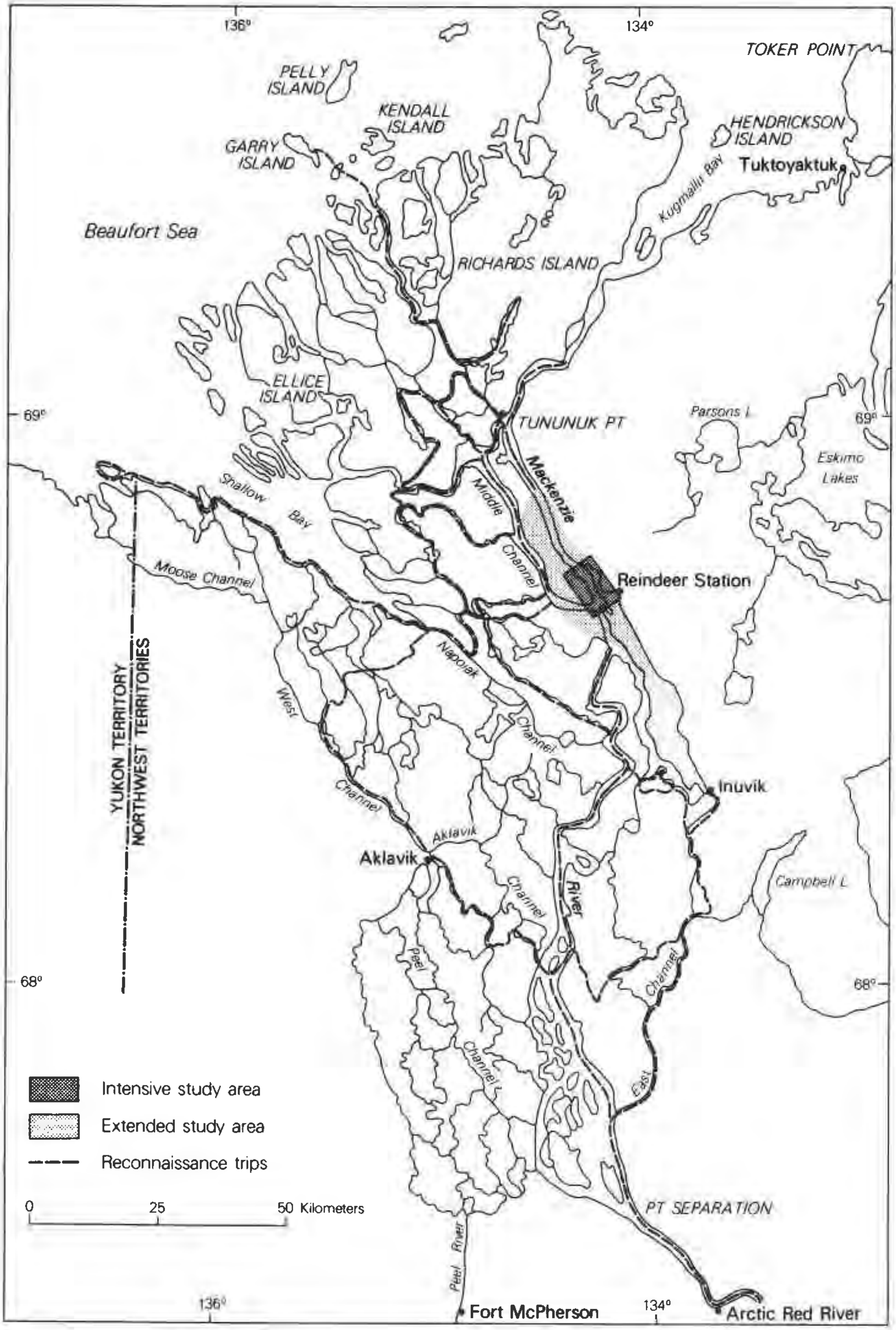

FIG. 1. Study area within the modern Mackenzie River Delta.

averages 11 cm each summer, and snowfall averages 173 cm, for a total annual precipitation of about 25 cm. Most of the precipitation during the summer months is in the form of rain, the maximum usually occurring in July or August. Although rainfall is light, thunderstorms occur infrequently and stations during such storms may record rainfalls of 1.3 cm or more in 24 hours.

Permafrost conditions in the study location have been described by Gill (1971; 1973*a*), Smith (1973), and Smith and Hwang (1973). On the basis of ground temperatures and site investigations, the Mackenzie Delta forms an outlier of the discontinuous zone. Permafrost is physically discontinuous and the maximum thickness is normally less than 100 m. The seasonally thawed layer varies in thickness depending upon topographic position and plant cover; the depth-to-permafrost may be more than 1.5 m in pioneer equisetum (*Equisetum fluviatile*) communities located on the leading edge of slipoff slopes to often less than 0.5 m in climax white spruce communities situated on the upper segments of levees (Fig. 2).

Vegetation of the study area has been described by Gill (1972; 1973*b-d*; 1974*a-b*). The climax white spruce stand under study is typical of the Mackenzie Delta's old-growth forests that occupy the higher levees (Figs. 2, 3). Average tree height is 12 m; diameter at breast height (dbh) ranges from 18 to 30 cm; canopy density is 60 to 70%; tree ages range from 170 to 290 years. The stand has a relatively sparse, 3.5–4.5 m tall willow (*Salix glauca*, *S. arbusculoides*, *S. pulchra*, *S. richardsonii*) and alder (*Alnus crispa*) understory. Ground cover consists of a thin layer of the mosses *Hylocomium splendens* and *Aulacomnium palustre*, covering 80% of the surface. The remainder of the ground is overlain by a thin mor layer interspersed by patches of exposed sediment and several thick cushions of the mosses *Drepanocladus uncinatus*, *Campylium stellatum*, and *Bryum pseudotriquetrum*.

Purpose

The purpose of this paper is to present the hypotheses that in the Mackenzie River Delta, individual spruce trees may cause small bowl-shaped depressions in the permafrost table below them through the interaction of the following processes:

1. Spruce trees intercept a portion of the rainfall by their crowns, thereby reducing soil moisture below them, which improves heat conduction through the soil and increases the thickness of the active layer.

2. Trunks of spruce trees reduce the velocity of overbank flow during floodstage, thereby causing more sediment to be deposited near the trunk. This smothers the growth of highly insulative and moisture-retaining mosses near the trunk, and at the same time creates small raised cones of alluvium which, because of their relief, have better drainage and intercept more solar radiation. Both increase heat conduction downward through the soil in the vicinity of the trunk to increase active layer thickness.

Procedure

The following methods were used to quantify the influence of white spruce trees on the topography of the permafrost table:

1. From 30 June to 4 September 1966, gross rainfall, throughfall, and stemflow were sampled in a radiating grid beneath one randomly chosen white spruce tree within a stand with a spatial distribution similar to that illustrated in Fig. 3. Gross rainfall was sampled with two standard U.S. Weather Bureau 8 in. (20.4 cm) rain gauges placed in an unobstructed open area near the study site. Throughfall was measured at ground level with 20 10.5 cm diameter, no. 3 cans; stemflow was sampled with four no. 3 cans flattened against the spruce stem at a height of 1.2 m. Figure 4 shows rain gauge locations. Samples were taken in a similar fashion from a second (paired) randomly selected plot to test the representativeness of the intensive study plot. A different sample location was selected after each rainfall.

2. Snow-depth measurements were taken in February 1967. Other observations were made in March 1972.

3. In conjunction with the precipitation measurements, soil moisture values were measured 24 hours after a light rainfall of 1.14 mm in late summer to sample the influence of interception on soil moisture beneath spruce trees. In early September 1966, 20 soil samples were taken from beneath the tree shown in Fig. 5. Soil within the mineral horizon (beneath the mor layer) was sampled at a depth of 2.5 cm and at 15 cm intervals. Similar measurements were

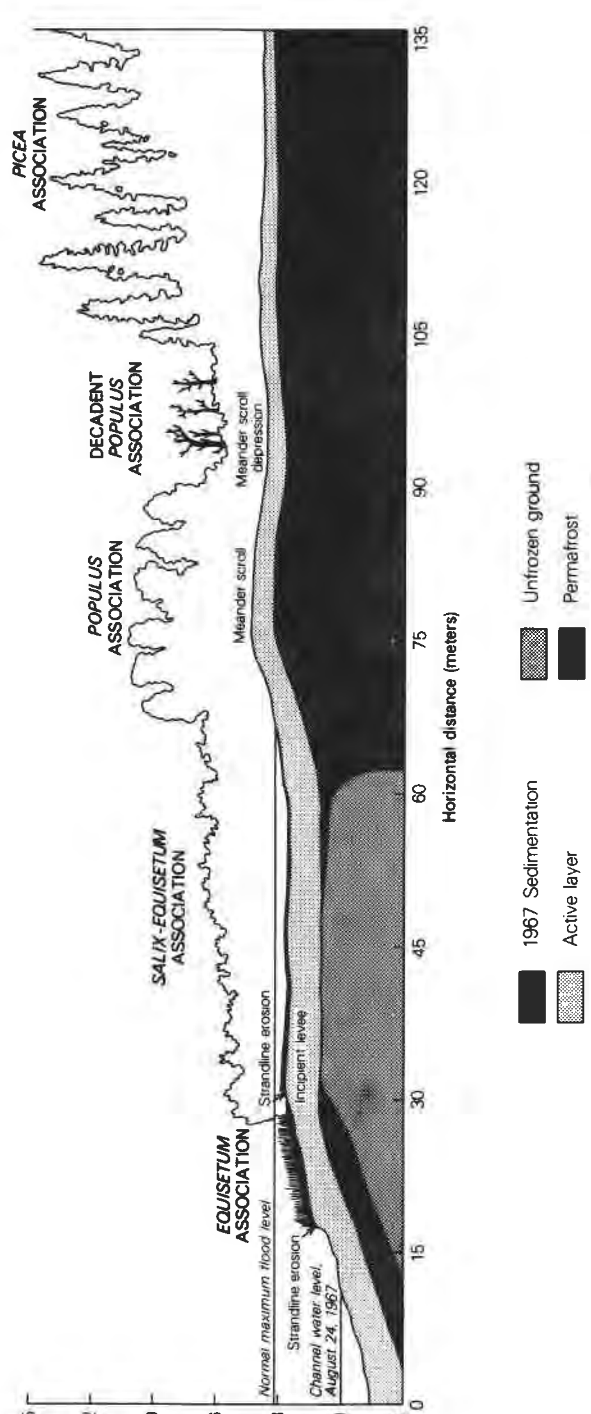

FIG. 2. Typical active layer thicknesses in successional plant associations of the Mackenzie River Delta.

FIG. 3. Climax stands of white spruce (*Picea glauca*) on higher levees in the Mackenzie River Delta, with a canopy density of 60 to 70%.

taken in another sample plot for comparison. Moisture percentages were later determined at the Inuvik Research Laboratory through the standard method of weighing, drying, and reweighing, as given by Gardner (1965).

4. Depths-to-frost around the tree shown in Fig. 5 were probed by a metal rod on 3 September 1966, after the active layer had reached its maximum thickness; these depths were tied to a survey grid so that a surface contour map (Fig. 6) and a permafrost-table map (Fig. 7) could be constructed. To check the representativeness of the study location, active layer thicknesses near some 30 additional trees were probed during September 1966, August 1971, and July 1974.

Results

Precipitation

Twenty separate rainfalls during the sample period produced a total of 65 mm of precipitation in the open site, and some 50 to 75 mm of gross rainfall in the study plot (Fig. 4) and paired sample plots. Gross rainfall during individual storms varied from .13 to 20.6 mm.

Throughfall ranged from 0 to 25 mm, depending on the location beneath tree crowns (Fig. 4). The ground area directly below the trees received approximately 15% of the gross rainfall. This loss was compensated to some extent by water that concentrated below the periphery of crowns through shedding and leaf-drip (Figs. 4, 5), so that the total amount intercepted is calculated to be in the order of 25%.

Stemflow during the period of measurement was negligible; only trace amounts occurred during the three heaviest storms. Additional observations during storms of varying intensities in the summers of 1971 and 1974 indicate that very little stemflow, if any, reaches the floor of spruce stands; trunks remain dry even during prolonged rainfalls.

Throughfall and stemflow in the moving sample plot compared favorably with data gained in the stationary plot: measurements were within ±6% of each other.

Limited information gathered on the amount of snow interception by trees indicates that during the relatively windless winters of the Mackenzie Delta, about 40% of the snow that falls on this stand is intercepted and held by spruce crowns. The February 1967 measurements, which are similar to measurements taken in March 1972, are shown in Fig. 5.

In all, the amount of rainfall intercepted by the spruce canopy in the study area accounted for an approximate loss of 16 mm of water, or 25% of the gross rainfall of 65 mm. This is the same figure given by Patric (1966), who reported

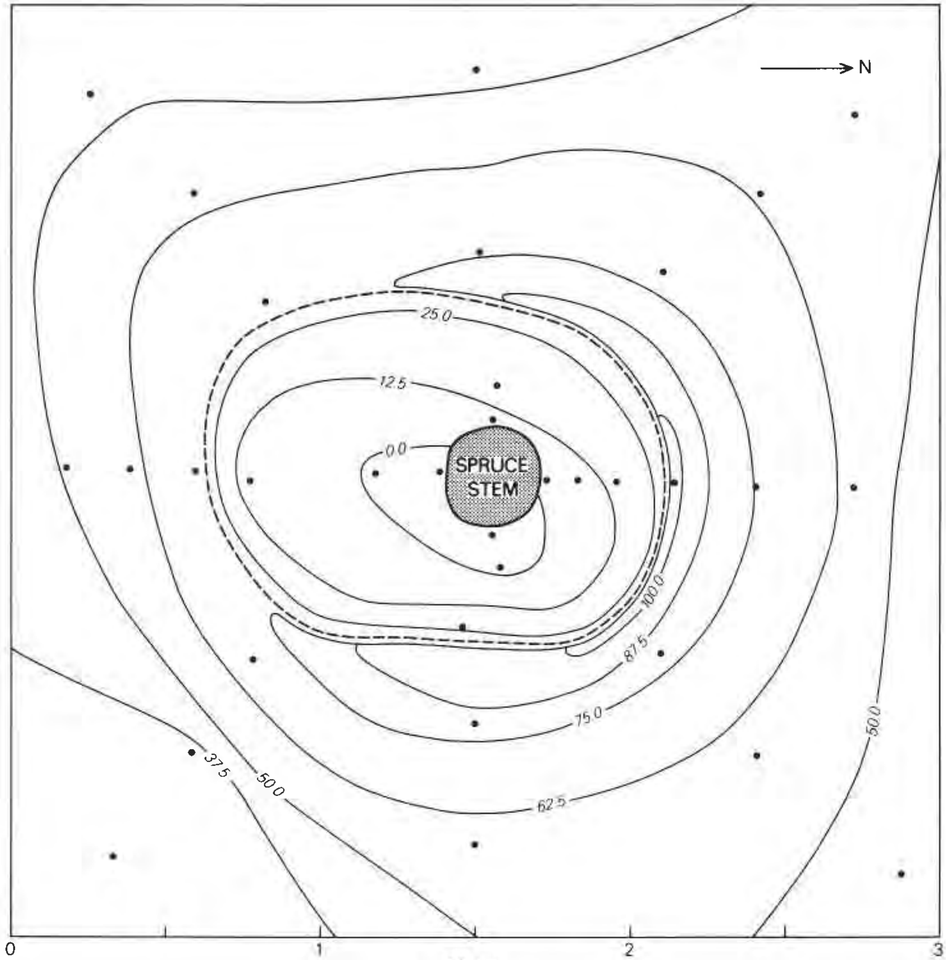

FIG. 4. Isohyet map showing the influence of a white spruce crown on the distribution of rainfall in the study area.

an interception loss of 25% of the annual rainfall in a mature stand of western hemlock (*Tsuga heterophyla*) and sitka spruce (*Picea sitchensis*) in southeast Alaska.

Soil Moisture

Results of the soil moisture measurements are summarized in Fig. 5; soil moisture ranged from 30% at a distance of 1.5 m from the edge of the crown-protected area to 16.5% within the most protected location adjacent to the trunk. The graphed values shown in Fig. 5 compare favorably with measurements taken in a second plot on the same date; the spatial variation in soil moisture was similar (depressed toward the tree trunk) and moisture values were of the same order (generally within $\pm 4\%$ of each other).

These data thus illustrate that rainfall interception by the forest canopy may cause considerable spatial variation in soil moisture. As expected, 24 hours after a rainfall, the soil was drier beneath a tree than away from it. However, the fact that the soil after a very light rainfall was nearly twice as moist away from the protected area as it was directly below the crown, suggests a seasonal rather than a temporary

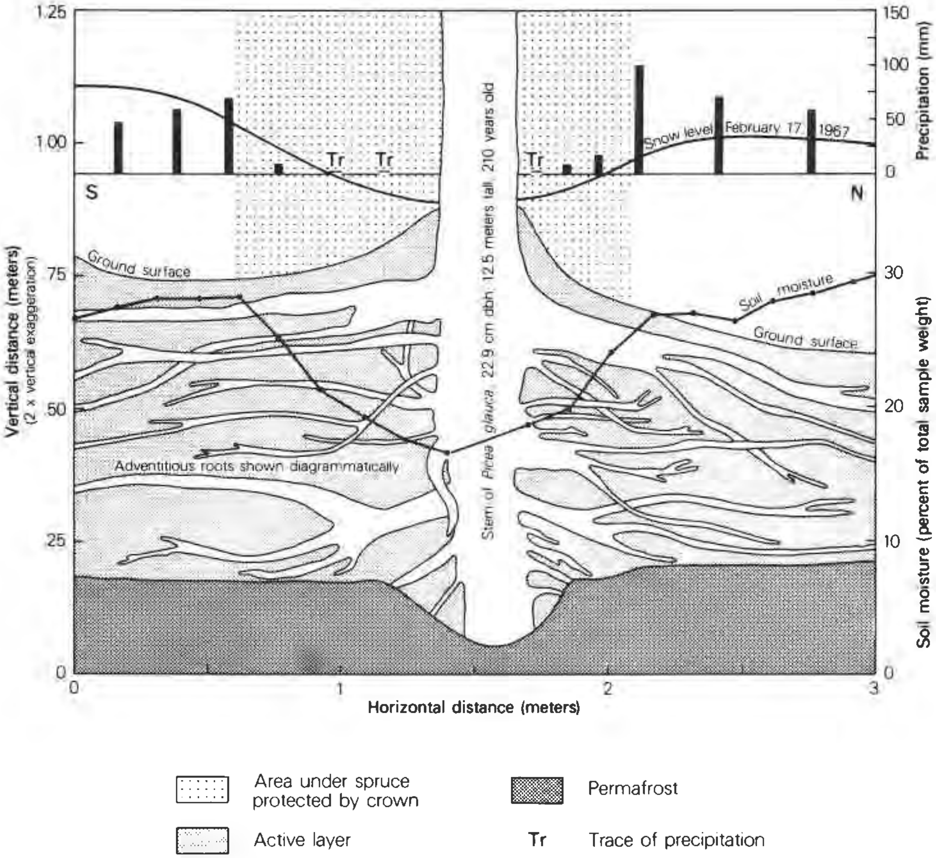

FIG. 5. Pattern of precipitation and soil moisture as influenced by the crown of a white spruce tree; depression of frost table near stem of tree.

condition. Also, the distribution of the near-surface soil water suggests that moisture changes are not due to extraction by tree roots. It thus appears that in addition to the normal loss of soil moisture through evaporation and transpiration, an interception of 25% of the summer precipitation by crowns will cause a similar reduction in soil moisture below trees.

The Permafrost Table

Unlike many other regions that are underlain by permanently frozen ground, the permafrost table in the Mackenzie Delta is remarkably uniform. Undulations in the frost table are minor and are associated primarily with surface topography and ecosystem type (Fig. 2). One of the more important reasons for a uniform permafrost table is associated with the soil and vegetation of the delta. The Mackenzie Delta is underlain by alluvium that is relatively uniform in texture, normally ranging from silty clay to silt loam (Gill 1971), thus moisture retention and heat diffusivity through the soil are similar. Adding to the uniformity of the surface environment, each plant association in the study area creates a similar amount of biomass and organic material at the ground surface. Because soil surface conditions are similar, frost table undulations are minimal.

Variations in permafrost-table microtopography are found only near the buried stem and adventitious roots[2] of white spruce. Permafrost near the stem of the spruce shown in Fig. 5 is depressed some 12 to 15 cm below the adjacent

[2]In alluvial landscapes that are underlain by permanently frozen ground, sediment deposition is accompanied by a rise in the permafrost table. Plants growing in such locations are forced to place lateral roots from the buried lower portion of their stem into the constantly elevating active layer, otherwise the rise in permafrost would engulf the roots and kill the plants. Such adventitious roots are shown diagrammatically in Fig. 5.

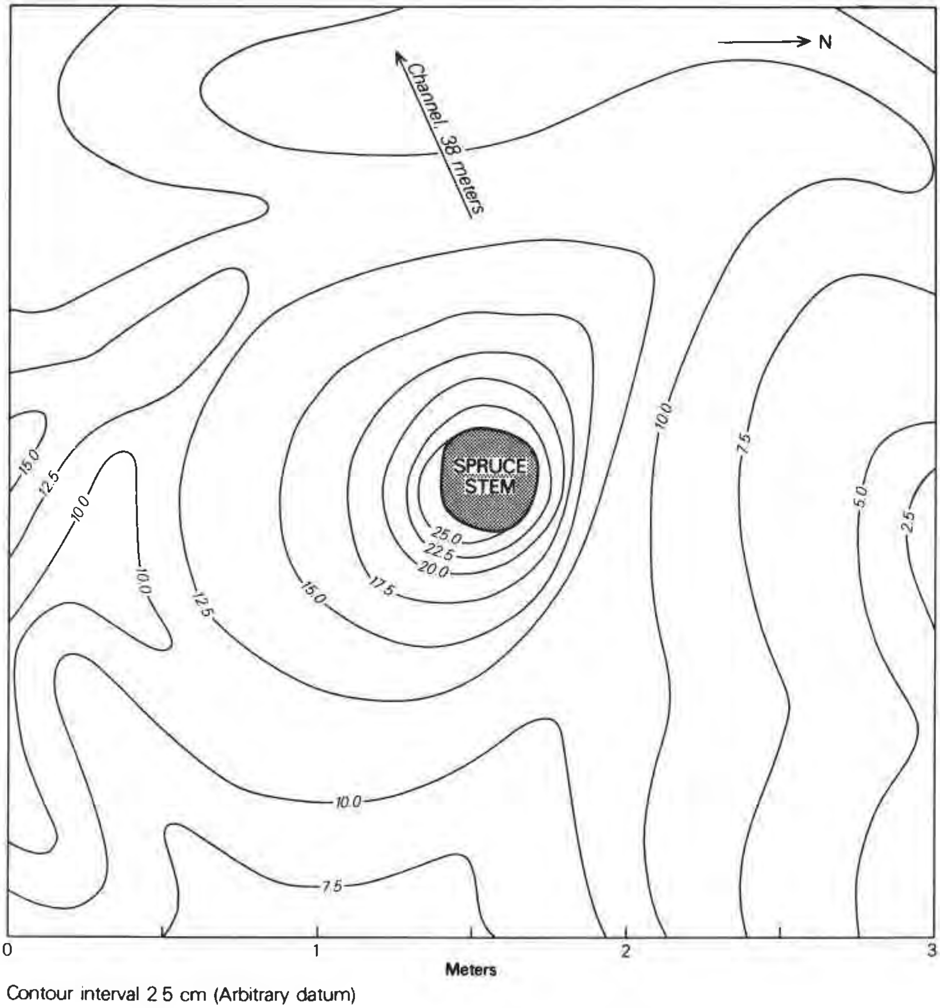

FIG. 6. Contour map of ground surface showing sediment buildup around stem of spruce.

level of the frost table. Figure 7 is a contour map of the same site, which shows that the stem is ringed by a bowl-shaped depression similar to the hollows that form in snow around tree trunks during sunny weather by melting and sublimation. While this depression is only some 15 cm below the general frost table, it has formed despite an alluvial-induced rise in ground level near the trunk (Fig. 6). Thus while the average depth to permafrost at the study site was 54 cm, the active layer near the base of the spruce tree had a true depth of 83 cm, for an increase of 54% over average.

Discussion

The localized depression of the frost table below spruce trees in the study area appears to result from the interaction of several factors:

1. Crowns of white spruce in the Mackenzie Delta are highly waterproof, and reduced amounts of soil moisture occur below them due to interception of rain, and to a certain extent, snow. Decreased soil water in that location enables greater heat diffusivity, resulting in a depressed frost table.

2. Wherever spring flood overbank flow is obstructed, such as near a spruce trunk, eddies form that cause accelerated sediment deposition near the obstacle. Figure 6, which is typical of this situation in the study area, shows a deposit that is raised 15 cm above the surrounding ground level. Such topographic rises have improved drainage, which would further decrease

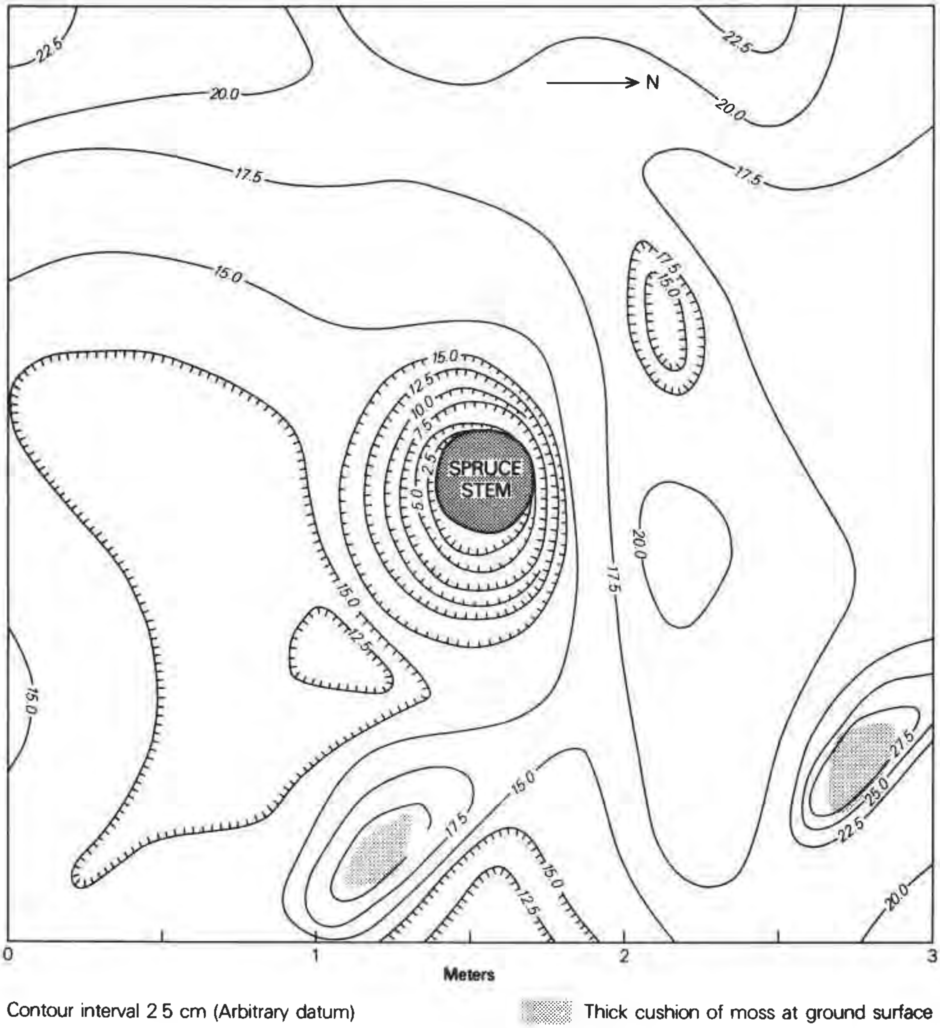

FIG. 7. Contour map of frost table directly beneath surface area of Figure 6 showing depression in permafrost near spruce stem and rise under cushions of moss.

the soil moisture near spruce trunks, and add to heat flow into the ground.

3. Accelerated sediment deposition around spruce trunks also has an effect on the ground's plant cover which ultimately affects the heat budget. Mosses are killed when alluvium is deposited on them (Gill 1971). Thus in the study area bryophytes seldom grow around the base of spruce trunks; instead, a cone of wet mud surrounds trees after a sufficiently high flood. The thermal conductivity (K) of wet peat is .0013 cal cm^{-1} s^{-1} $°C^{-1}$ (.0054 J cm^{-1} s^{-1} $°C^{-1}$), whereas the conductivity of wet mud is .002 (U.S. Army 1966), nearly twice as high. The physical presence of a tree trunk thus creates conditions of alluviation that reduce the growth of highly insulative mosses, which in turn causes greater downward heat penetration around the trunk, and a thicker active layer results. Even small patches of moss that are able to become established where alluviation is less may cause a rise in the permafrost table. Figure 7 illustrates two such moss cushions where the active layer is 5 to 7.5 cm thinner under the moss cover than it is nearby. This is as expected, since the increased soil water and insulation afforded by a discrete moss cover results in a colder soil and a higher frost table.

4. Finally, depressions in the permafrost table surrounding spruce trees are normally oriented toward the south (Fig. 7). This suggests that the low-albedo south-facing 'slopes' of alluvial

deposits surrounding trees (the one shown in Fig. 6 drops 15.5 cm toward the south in 92 cm, for a slope of 10°) may intercept more solar radiation than the vegetated (and higher albedo) flat surfaces away from the trunks (numerous sunflecks strike the forest floor during summer). This would also add to the heat budget of the area surrounding tree trunks, which would be reflected in a depressed permafrost table.

Conclusion; Need for Further Research

It must be pointed out that testing of the hypotheses presented here is incomplete; while data have been gained during this study on rainfall interception, soil moisture, and active layer thickness, there must ultimately be measurements of net radiation, soil heat flux, and other heat budget parameters before it is known precisely which of the mechanisms presented here is most responsible for the depressed frost table below spruce trees in the Mackenzie River Delta. Such field studies, which are not yet out of their infancy in northern Canada, would add considerably to our incomplete understanding of the interactions of vegetation and soil frost phenomena.

Acknowledgments

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