

scientist it means that he has more to do and a more important part to play. The very real problems that face development in the North mean that the role of research is correspondingly greater.

"... 10 to 15 years hence... we should expect northern mineral wealth to find entry into the world market on a real and large scale. I suggest that Canada has this decade before her in which to make ready to produce and sell northern products. What Canadians must do is learn how to operate in the North efficiently. I am not sure that our northern research programs are all the right ones, or that adequate co-ordination is being done. We need to look at all this more closely. We need to make sure that young men and women are training for northern scientific work, — and that they have opportunity to get at it. This is what industry is doing in every field. In 1965 research is the key to industrial competence. On industrial competence depends standards of living, cultural values, even nationhood. It is the number one must."

RELATIONSHIP OF WHITE SPRUCE TO LENSES OF PERENNIALY FROZEN GROUND, MOUNT MCKINLEY NATIONAL PARK, ALASKA

Introduction

Permafrost underlying the boreal forest creates unusual conditions of succession and climax. The insulating effect of vegetation often results in modified permafrost characteristics, which in turn influence patterns of plant growth. This study reports an investigation of permafrost lenses beneath individual white spruce trees growing on a terrace of the McKinley River in Mount McKinley National Park, Alaska, and suggests ways in which permafrost may form under vegetation where it has previously been absent. The relationships here studied are thus important to the boreal ecologist who is interested in vegetation cycles.

The McKinley River is on the north side of the Alaska Range and originates from melting ice of the Muldrow Glacier. The river is typical of braided glacial streams in Alaska, has a steep gradient, and carries a large sediment load. During Recent times, between 200 and 300 years ago, the Muldrow Glacier was at a maximum extent and the ice front was in a position marked today by an extensive terminal moraine. At that time outwash from the river formed at a higher level than it does now. As the glacier receded, the origin of the river retreated further up the valley, the river load was lessened, and the stream gradient changed, leaving terraces along the river that were subject to annual flooding. These terraces are generally composed of coarse gravel similar to that found along the braided stream at the present river level.

The white spruce (*Picea glauca* (Moench) Voss) stand described in this paper is on one of these terraces, 12 km. from the terminus of Muldrow Glacier at an elevation of 550 m. The terrace was formed during a maximum advance of Muldrow Glacier; the river has since cut down several feet into the gravel outwash leaving the terrace undisturbed for the past 250 to 300 years.

Climate

The climate of the McKinley River area is continental although the temperature extremes are not as great as in the interior lowland forests north of the Alaska Range. Records were kept for a short period at the Wonder Lake Ranger Station and these have been correlated with those at McKinley Park, which has a 30-year record. Precipitation averages approximately 515 mm. per year with a maximum in late summer (August, 80 mm.) and a minimum during the winter months (March, 25 mm.). Snow accumulation in the forest during the winter varies from 0.5 to 1.5 m. The mean annual temperature is approximately -4.6°C .; January is the coldest month with a mean temperature of -19.0°C . while July is the warmest with a mean temperature of $+11.5^{\circ}\text{C}$. The area is within the zone of

Table 1. Monthly mean temperature and precipitation for Wonder Lake (63°28'N; 150°52'W. Elev. 610 m.)

	Temperature °C.	Precipitation mm.
January	-19.0	35
February	-16.6	30
March	-13.6	25
April	- 4.8	30
May	+ 3.4	32
June	+ 9.8	60
July	+11.5	69
August	+ 9.0	80
September	+ 3.9	51
October	- 5.3	39
November	-14.8	34
December	-18.6	30
Year	- 4.6	515

discontinuous permafrost. Table 1 summarizes weather data from Wonder Lake, about 5 km. north of the study area.

Vegetation

The stand of white spruce on the McKinley River lies close to the altitudinal limit of timber in the region. It is the highest extensive stand of large spruce on the McKinley River alluvium, but both white and black spruce (*Picea mariana* (Mill.) B.S.P.) are found to elevations of 750 m. on the south-facing slopes to the north of the river. Stands of balsam poplar (*Populus balsamifera* L.) are found on alluvial deposits along the rivers and adjacent to some of the numerous small morainal ponds. Most of the upland area adjacent to the McKinley River is underlain with permafrost and covered by a low shrub birch (*Betula glandulosa* Michx.) — moss type, often referred to as shrub tundra or dwarf birch tundra. Areas of poor drainage in this zone are occupied by tussocks of the arctic cottongrass (*Eriophorum vaginatum* L.). Above 900 m. the vegetation consists primarily of low matted alpine tundra.

The stand in which the perennially frozen lenses occur is an open white spruce-sphagnum type with an appearance more typical of black spruce than white spruce. Examination of several hundred trees showed that all but one on the river terrace are white spruce

even though black spruce occurs on the slopes around the stand in the vicinity of Wonder Lake, only a few kilometres to the north.

The vegetation of the stand is heterogeneous because of the variety of micro-habitats present. The surface is irregular with many mounds, especially beneath trees. On the drier sites created by these mounds is a thick moss mat of *Hylocomium splendens* (Hedw.) B. and S., *Tomenthypnum nitens* (Hedw.) Loeske, and *Pleurozium schreberi* (Brid.) Mill, a few scattered lichens (mostly *Cladonia rangiferina* (L.) Web., *Peltigera aphthosa* (L.) Willd., and *P. canina* (L.) Willd.), low shrubs of narrow-leaved Labrador tea (*Ledum decumbens* (Ait.) Lodd.), bog blueberry (*Vaccinium uliginosum* L.) and low shrub birch.

In the depressions between the trees is a thin cover of mosses (primarily *Sphagnum warnstorffiana* Dr. and *Aulacomnium palustre* (Hedw.) Schw.), a few scattered willow shrubs (mostly *Salix richardsonii* Hook.), and a large number of low shrubs and herbs, the most important being netleaf willow (*Salix reticulata* L.), swamp cranberry (*Oxycoccus microcarpus* Turzc.), variegated horsetail (*Equisetum variegatum* Schleich.), northern single-spiked sedge (*Carex scirpoidea* Michx.), fragile sedge (*Carex membranacea* Hook.), white cotton grass (*Eriophorum scheuchzeri* Hoppe), Scotch asphodel (*Tofieldia pusilla* (Michx.) Persoon), northern grass of Parnassus (*Parnassia palustris* L.), and three flowered rush (*Juncus triglumis* L.). Frost scars, often with standing water, are in all stages of re-vegetation by sedges and mosses.

The open-grown white spruce range in size from seedlings less than 5 cm. tall to mature trees 9 m. high and 16 cm. in diameter. I arbitrarily separated trees into two size classes based upon diameter at 1 m. above the ground: 5 cm. and larger (poles), and less than 5 cm. (saplings). Average stand density per 100 sq. m. is 9.8 poles and 19.8 saplings.

Tree ages range from a few years to 209 years. Of 36 sampled pole-size trees,

27 (80 per cent) are between 100 and 140 years old: only two are less than 100 years. Of 51 saplings, 36 (71 per cent) are between 10 and 39 years old, and only two are older than 100 years.

Growth in the stand is slow with an average annual diameter increment in the trees of 0.7 mm. The slow growth rate and the presence of an average of 4.4 dead trees per 100 sq. m. indicate that conditions within the stand are far from optimum for white spruce.

Parent material

The parent material of the stand consists of at least 1.5 m. of silty clay over river gravel. Mechanical analysis shows the silty clay to be uniform to a depth of at least 70 cm. and to consist of 15 per cent sand, 43 per cent silt, and 42 per cent clay. The pH of the material varies from 7.0 to 7.5 and there is no alteration near the surface although the decaying moss mat just above the clay has a pH of approximately 5.0.

There is no true development of a soil profile in the stand. Because of the impervious nature of the silty clay substrate, water accumulates in the depressions. Few roots penetrate more than a few centimetres into the silty clay, but rhizomes of variegated horsetail are found to depths of 1 m. An organic layer consisting of decaying mosses is 10 to 20 cm. thick and rests loosely on the mineral soil surface.

An interesting phenomenon of the parent material in the stand is the presence of scattered pockets of rocks. These have probably been brought to the surface from the lower layers of gravel through frost action. A few of these sorted pockets are bare, while others are covered with vegetation. In some cases, pockets of rocks were found directly under trees. A cross section through these rock pockets shows that they are isolated on the surface with silty clay on both sides and beneath them. I was unable to determine whether the sorting had taken place before the surface was vegetated or afterwards, but the absence of vegetation on some of the rock pockets and the presence of bare frost scars within

the stand indicate that frost action and soil movement are currently taking place.

The frozen lenses

The older trees in the stand are situated on conspicuous mounds 2 to 4 m. in diameter with steep sides 50 to 100 cm. high (Fig. 1). The upper surface is flat to slightly convex in most of the mounds but in a few cases the upper surface is depressed in the middle so that the mounds somewhat resemble doughnuts. All of the mounds are covered with a thick moss mat of *Hylocomium splendens* and *Pleurozium schreberi* through which are growing several ericaceous shrub species and bog birch. The mounds are symmetrical in most cases with the tree in the centre. In a few instances I observed compound mounds where two trees, growing closely together, are on one mound.

Profile cross sections were made through five of the mounds. In each case the centre of the mound consists of an isolated lens-shaped core of frozen silty clay (Fig. 2). The lenses are, on the average, 2 m. in diameter, have their upper surfaces 20-30 cm. above the surrounding silty clay surface, and are about 50 cm. to 1 m. thick. The upper surface is nearly flat at the centre and steepens abruptly at the edges. The lower surface has approximately the same shape as the upper surface.

Above the frozen lens is 20 cm. of unfrozen silty clay overlain by 20 to 30 cm. of organic material and moss. The roots of the trees are primarily distributed in the organic layer and follow the contours of the mound.

Examination of the frozen lens showed it to be composed of alternating layers of silty clay and pure ice. Taber¹ and Beskow² have described this phenomenon in seasonal and permanently frozen grounds and referred to it respectively as "ice gneiss," and "stratified frozen soil." It occurs most commonly where fine sediments with considerable moisture are frozen. Upon exposure to the atmosphere the ice melts and the frozen silty clay thaws resulting in a slumping and general subsidence of



Fig. 1. Conspicuous mound surrounding two white spruce. Bands on pole are 1 dm. in width.

the mound. Where the moss mat remained undisturbed, the upper surfaces of the frozen lenses were within 30 cm. of the moss surface at the end of August. It is presumed that the lenses remain frozen the year round.

Discussion

Lenses of permafrost appear to form because of some difference in the heat regime of the soil under the trees as compared with that between the trees. I suggest two possible explanations for the colder temperatures under the trees. Less snow usually accumulates under coniferous trees than in the adjacent area between trees. Pruitt³ has shown that winter temperatures 1 inch (2.5 cm.) below the moss surface are lower near the trees than they are under the surrounding deeper snow. In one instance he reported the temperature close to the tree to be -6.5°F. (-21.25°C.) while that under the deeper snow was $+10.5^{\circ}\text{F.}$ (-12.0°C.). Less snow cover under the trees with the resulting lowering of soil temperature in the winter

could be sufficient microclimate difference to cause the ground to remain frozen throughout the year.

The moss layer is thicker on the mounds under the trees than it is in the area between the trees. The green and decaying moss layer on five mounds averaged 29 cm. in depth with a range of 18 to 35 cm., while that surrounding the mounds averaged 10 cm. with a range of 4 to 13 cm. Benninghoff⁴ reports that a dry moss layer in summer acts as an excellent insulator. When saturated and frozen, as it is during most of the winter, the moss layer insulates inefficiently. A thick moss layer is important in maintaining a permafrost layer close to the surface in many areas of the Arctic and Subarctic where disturbance of the moss layer usually results in a recession of the frozen ground beneath the disturbed area.

The mound is created as the silty clay freezes. When fine soil such as silt or clay freezes, ice is segregated into layers of pure crystals. Water is then drawn to these layers from below. This process

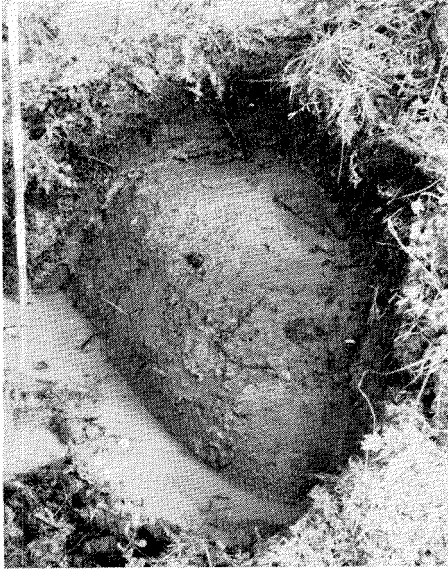


Fig. 2. Frozen silty clay in centre of tree mound. Water remains on the surface of the impervious silty clay.

is described by Beskow.² Taber^{5,6} has placed cylinders of clay in water and frozen them from above. He found that the height of the frozen cylinders increased over the original length by as much as 60 per cent by the addition of horizontal lenses of pure ice. These experimental conditions are very similar to the natural conditions on the McKinley River terrace: a fine textured soil, abundance of moisture, freezing temperatures from above.

Taber¹ has shown that "ice gneiss" from a depth of 3 to 6 ft. (0.9–1.8 m.) near Nome contained 80 per cent ice by weight. In another instance he noted that the subsidence of silt overburden due to melting was equivalent to a shrinkage in volume of 40 per cent and concluded that the total amount of ice by volume in the original material was 58 per cent. Péwé⁷ recorded 315 per cent moisture by weight in frozen silt in the Fairbanks area. I was unable to determine accurately the amount of ice in the silty clay material in the frozen lenses, but I estimated that the samples, when thawed, contained about 50 per

cent water by volume. The incorporation of this amount of water as ice into the frozen silty clay would increase the volume enough to account for the formation of the mound.

The formation of such mounds under the trees creates an unstable condition. The increased size of the expanding lens causes cracks in the surrounding moss layer. This, in turn, breaks the insulating layer of the moss and causes the lens to melt, usually on one side. The tree may then remain alive with a hollow space beneath it or it may tip partially over and subsequently die. In some cases it appears that the formation and expansion of the frozen lens is enough to break roots and tip trees. In other cases the lens collapses completely, leaving a small pool of water under the tree and a bare surface on the disturbed side. Some root systems are so disturbed that wind-throw results.

From the evidence presented above, I propose that there is a vegetation cycle within the stand (Fig. 3). Seedlings and saplings are found on and adjacent to the frost scars, the seeds germinating primarily on the exposed clay surfaces or the disturbed edges. White spruce

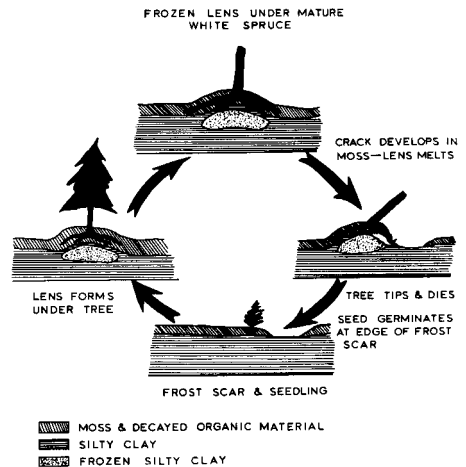


Fig. 3. Cycle of development and collapse of tree mounds. Seedlings germinate on frost scar or bare surface created by melting of the frozen core in the mound.

seedlings rarely become established on thick moss mats. As the young trees grow, mosses develop beneath them, and a frozen lens forms under the tree. Lens and tree develop together to form a tree mound. Eventually the mound is disturbed through the cracking of the moss layer, the mound collapses, and a disturbed surface results. Spruce seedlings germinate on this surface and may eventually develop a new tree mound.

It is difficult to predict the future status of the stand. The terrace is only 250 to 300 years old, so the stand should probably be considered as a successional one. There has been little development of a climax soil. It is impossible to determine whether the tree mounds will persist, whether there will be a larger cyclic development from spruce to bog to spruce again as Drury⁸ described for the Kuskokwim River, or whether the stand will become stabilized as a white spruce stand, a sphagnum bog, or some other vegetation type.

Summary

Perennially frozen mounds have developed under white spruce growing in silty clay. The frozen lens is thought to result from the insulating effect in summer of a thickened moss mat and from soil cooling in winter as a result of a thin snow layer under the trees. The mound is created through expansion of the silty clay caused by incorporation of water into the lens as thin layers of clear ice. Disturbance of the moss mat results in a melting of the lens, a collapse of the mound, and often the death of the tree. As new trees develop, new mounds and frozen lenses develop in the soil beneath them.

Acknowledgement

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