Snow and Ice Roads: Ability to Support Traffic and Effects on Vegetation

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ABSTRACT. A study was made of the effects of construction, and use by wheeled vehicles, of snow and ice roads at a test site near Norman Wells, N.W.T. Peat was compressed as a result of these operations. The proportion of the test roads covered by live plants was about 12% in the first summer after construction and increased to about 35% in the second summer. Land cleared of vegetation by hand was less disturbed than that cleared by machine, but machine clearing is tolerable if there is to be further disturbance. Ice-capped snow roads and ice roads, properly constructed and maintained, are shown to be capable of withstanding the traffic and loads to be expected during possible pipeline construction along the Mackenzie River Valley.

RÉSUMÉ. *Routes construites sur la neige et la glace: résistance à la circulation des véhicules et effets sur la végétation.* On a effectué à Norman Wells, dans les Territoires du Nord-Ouest, une étude portant sur les effets de la construction de routes sur la neige ou la glace et sur les effets de la circulation des véhicules munis de roues sur ces routes. Les travaux réalisés ont eu pour effet de comprimer la tourbe. La proportion des routes recouvertes de végétation était de 12%, l'été suivant la construction, et a augmenté à environ 35%, le deuxième été. Le débroussaillement manuel de la végétation s'est avéré moins nuisible que le débroussaillement mécanique; cependant, on pouvait tolérer le débroussaillement mécanique si l'on devait causer d'autres bouleversements par la suite. Il est apparu que les routes de glace ou recouvertes de glace, lorsqu'elles étaient bien construites et bien entretenues, pouvaient résister à la circulation et aux charges des véhicules qui emprunteraient ces routes lors de la construction éventuelle d'un pipeline dans la vallée du Mackenzie.

Резюме. *Снеговые и ледяные дороги; их устойчивость при эксплуатации и воздействие на растительность.* Велось изучение воздействия строительства и использования колесного транспорта на снеговых и ледяных дорогах в районе опытного участка около Норман Уэллс, Северо-Западные Территории. В результате этих экспериментов торфяник был утрамбован. Пропорция опытных дорог, покрытых живыми растениями, составляла приблизительно 12% в первое лето после сооружения дороги и возрастала иприблизительно до 35% во второе лето. Ручное уничтожение растительности наносило меньший вред, чем машинная очистка дорог, однако, применение машни допустимо при последующей эксплуатации дорог. Было показано, что хорошо иостроенные и правильно поддерживаемые обледенелые снеговые и ледяные дороги способны выдерживать плотность движения и нагрузки, ожидаемые в иериод сооружения трубопровода в долине р. Маккензи.

INTRODUCTION

Canadian Arctic Gas Pipeline Limited (C.A.G.P.L.) has made an application to transport natural gas from Prudhoe Bay, Alaska to the south by means of a buried, chilled pipeline passing via the Mackenzie Delta, N.W.T. and the Mackenzie River

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Valley. Foothills Pipe Lines Ltd. (Foothills) has submitted a competing application to provide a similar pipeline — entirely within Canada — from the Mackenzie Delta to the south. Both proposals have given rise to concern about the effects of pipeline construction on the environment (Mackenzie Valley Pipeline Inquiry 1974-1976). In regions underlain by permafrost, the passage of vehicles directly over the ground surface, even in winter, cannot be tolerated, regardless of whether the surface is graded or not. Using winter roads of snow or ice has been proposed as one way of protecting the ground surface (C.A.G.P.L. 1974a; Foothills 1975). In this paper are reported the results of tests at Norman Wells, N.W.T. to determine whether winter roads can withstand the amounts and types of traffic associated with pipeline construction, and to evaluate the environmental effects of using winter roads.

SITE DESCRIPTION

The Norman Wells winter road test site is located about 500 metres northeast of the east end of the Norman Wells airstrip. A gravel road to the Norman Wells quarry at Kee Scarp provides access to the site (Fig. 1).

Norman Wells is situated near the northern limit of the upper Mackenzie section of the boreal forest region (Rowe 1972). The test site is located in a mature community of black spruce, tamarack, red-fruit bearberry and feathermosses. Black spruce (*Picea mariana*) is the principal tree species. Typically, the spruce are 8-14 m tall and up to 120 years of age, with a canopy density of about 25%. Tamarack (*Larix laricina*) generally forms the main component of the upright shrub layer in the community. Other abundant shrubs include common labrador tea (*Ledum groenlandicum*) and other heaths, shrub birch (*Betula glandulosa*), several willows, and shrubby cinquefoil (*Potentilla fruticosa*). Ground cover is complete and consists of several low and prostrate shrubs, especially red-fruit bearberry (*Arctostaphylos rubra*), several herbs and an almost continuous layer of feathermosses (e.g., *Hylocomium splendens, Aulocomium acuminatum, Ptilium ciliare*).

Boreholes drilled along the southern edge of the winter-road test site indicate that peat, brown silt, dense brown gravel, and sand layers commonly overlie the hard shale bedrock beneath the winter-road test site (Pemcan 1972). The surface peat layer is up to 100 cm deep and is contained primarily within the active layer. No clearly-defined permafrost table exists, however, where the peat layer is more than 60 cm thick. Moisture contents as high as 340% (on a dry weight basis) have been measured in the soil. Ice occurs as finely-defined minute crystals, and occasionally as lenses up to 1.7 cm thick in random orientations (Pemcan 1972).

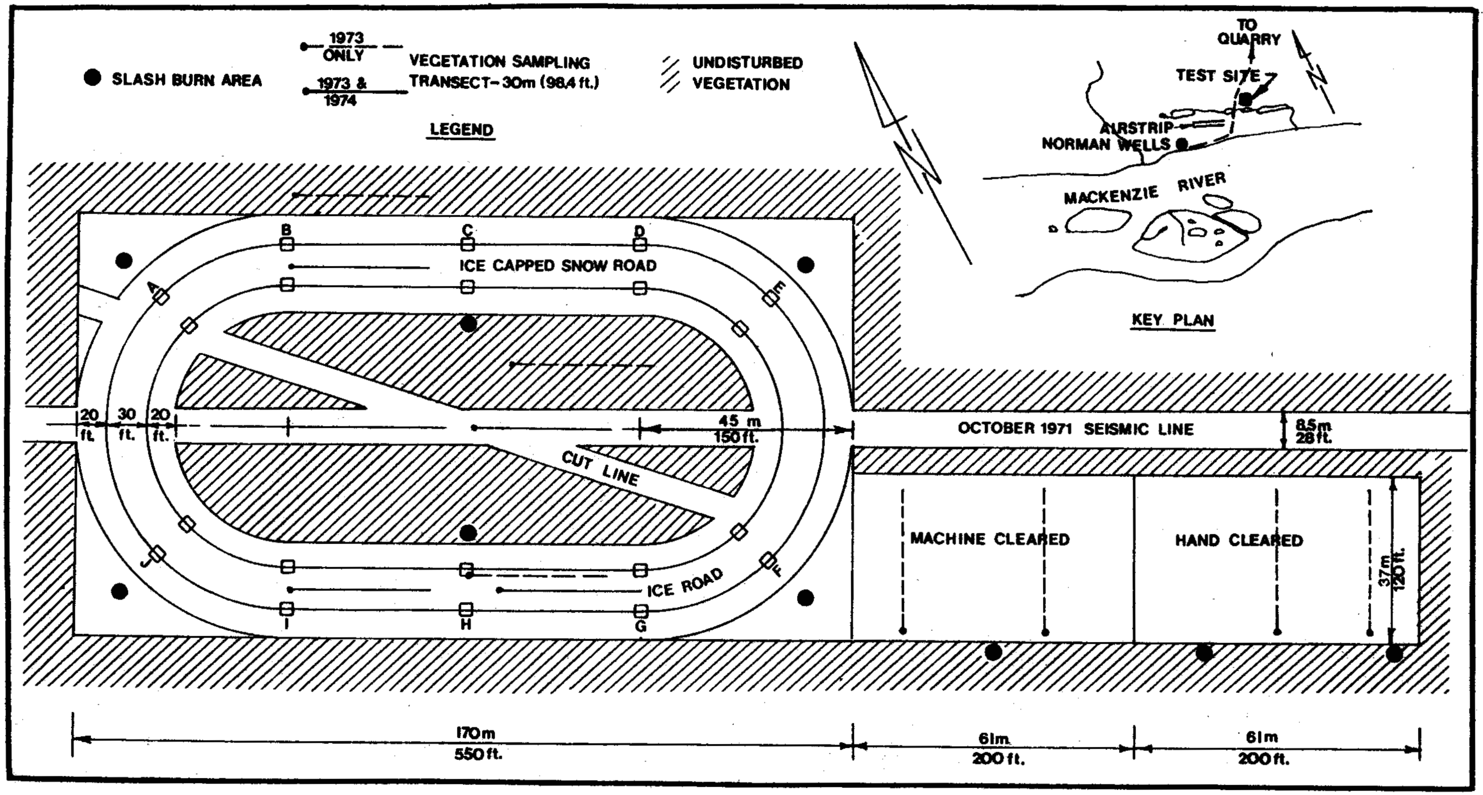
Sufficient excess ice existed (in the soil in the area) to cause subsidence of at least 30 cm along a seismic line cleared in October 1971 which bisects the winter-road test site (Fig. 1).

METHODS

Construction of the winter roads

The winter-road test site consisted of an elliptical loop about 350 metres in circumference (Fig. 1). It was constructed in late March 1973, neither the normal

FIG. 1. Layout and location of Norman Wells winter-road test loop.



nor the optimum time for construction of winter roads. In addition, the limited choice of construction equipment available at Norman Wells made it difficult to cope with some of the problems which were encountered. Vehicle specifications for the equipment used to build and test the winter-road loop are documented in Adam (1973a).

The test loop was cleared of vegetation with a bulldozer (D-7 Caterpillar). Two other areas beside the loop were also cleared — one by hand, the other by bulldozer to allow comparison of the effects of the two methods. The woody debris of cleared trees, shrubs and other slash was piled and burned directly on the snow on the nine sites shown on Fig. 1.

The first road surface to be built was one consisting entirely of compacted snow on the northern half of the test loop (Fig. 1). It failed to support much traffic, as was expected from experience gained as a result of the Joint Snow Compaction Program (1954), because of the lack of sufficiently heavy rollers and other equipment to thoroughly process the snow. When rebuilt, however, the road base could support passage of a tank truck along the inside edge. Water was sprayed onto the road proper. The resulting ice-capped snow road was tested as described below.

An ice road was built on the other half of the cleared loop (Fig. 1). All but 10 cm of snow were removed, the remainder being levelled with a large tire drag, leaving the surface smooth, the depressions filled with snow and the hummocks clear of snow. Over eight days, 200,000 litres of water were applied from a spray bar mounted on the back of water-tank trucks. Occasionally, water was pumped directly through the outlet hose to fill depressions in the road. The completed ice road was about 13 cm thick.

Road testing

Properties of both the ice road and the ice-capped snow road were sampled with Testlab's (1970) Swiss Rammsonde penetrometer kit (for measuring snow hardness), 7.5-cm coring auger kit, snow observation kit, and ice thickness kit. The snow was classified using the simplified snow classification method of the U.S. Army Corps of Engineers (see Garstka 1964). Samples were generally chosen at random although in some cases a complete cross-section of a traffic lane was sampled.

The test loop was subjected to traffic from 15 March to 1 April, then periodically on 6, 7 and 9 April before thaw ended use of the road. Most of the traffic travelled on the inside lane of both the ice-capped snow road and the ice road. However, due to the large number of vehicle passes, wheel loadings were distributed completely over the inside lane and extended partially over into the outside lane.

Test vehicles used were a 15-passenger van, three pick-up trucks, two intermediate-sized trucks, and three large tandem trucks with a capacity of about 10 cubic metres. In aggregate these nine vehicles made almost 36,000 circuits, travelling about 13,000 km. Following these tests with wheeled vehicles, a bulldozer with ice cleats travelled back and forth 100 times in a straight line over each road.

Vegetation sampling

In 1973, vegetation data were obtained by laying out 30-metre-long transects along, respectively, the undisturbed forest, the ice road, the ice-capped snow road, the hand-cleared area, the machine-cleared area, and the seismic line which bisects the test loop (Fig. 1). Twenty quadrats — two-metres square in the undisturbed forest, one-metre square elsewhere — were randomly located along each transect. In addition, transects were laid across the test roads at each reference station (A-J, Fig. 1) with one-metre square quadrats spaced alternately along the base line. The limited extent of the slash burn sites precluded the use of transects. Here, three one-metre-square quadrats were sampled in each of the nine burn sites. Cover estimates for each vascular species, mosses, lichens, litter, and dead moss/bare peat were taken in each quadrat sampled. In 1974, because of time limitations actual sampling was possible only at selected transects on the seismic line, the snow road, and both halves of the ice road (Fig. 1) with only 16 one-meter-square quadrats along each transect. (Notes alone were taken at the other sites.)

Depth of thaw was estimated in each quadrat by pushing a one-metre-long graduated metal rod into the ground as deep as possible. With this method, depth of thaw was underestimated because the rod often hit gravel or met with increased resistance in coarse soils; and, in some cases, the rod was completely pushed into the ground without encountering permafrost.

Height of both *Picea mariana* and *Larix laricina* in the undisturbed forest was estimated and their age determined with an increment core. Holes were dug in all areas to measure peat depth. Peat bulk density was determined gravimetrically from known volume cores (9.8 cm deep, 5.3 cm in diameter). The samples were weighed, dried at a temperature of 65°C for 48 hours, and reweighed.

Scientific nomenclature for vascular species follows Hultén (1968). Common names follow Viereck and Little (1972) for woody species and Hultén (1968) for other species.

Data were collected on 20-27 July 1973 and 8 August 1974.

RESULTS

Physical properties of the roads

Most of the 1972-73 snow pack was in place when construction of the test site began in early March 1973. Average snow depth was 49 cm in open areas and 56 cm in forested areas on 12 March 1973. In the forest, snow depth varied from 48 cm to 77 cm. The variation of snow characteristics with relative depth appeared uniform in both open and forested areas. At the surface the snow was fluffy, soft, dry, and new. Its coarseness increased uniformly throughout the upper 80% of accumulated mass to the depth at which 95% of the snow was classified as old, dry, coarse-grained granules greater than 0.2 cm in diameter. Below this the snow was in the form of depth hoar (0.3-1.0 cm in diameter).

Temperature profiles within the virgin snow were similar throughout the test site. With an air temperature of −20°C, snow temperatures ranged from −20°C at the surface to −18°C at a depth of 10 cm and −16°C below a depth of 20 cm.

Snow density generally increased with depth, except for the depth hoar layer at the bottom which was less dense than the layer immediately above it. Even though the depth hoar was in the form of clear, irregular ice particles, it was a highly porous layer.

Measurement of snow density and hardness is the most appropriate means of evaluating the ability of winter roads to support traffic (Joint Snow Compaction Program 1954). Snow density remains constant over a large range of freezing temperatures, but snow hardness (based on Rammsonde hardness number) is more temperature dependent. This number is an arbitrary index which indicates the resistance offered by snow to the vertical penetration caused by ramming a metal cone of given dimensions into the snow pack (see Clark *et al.* 1973 for detailed discussion of this).

Average depth of compacted snow was 28.2 cm on the snow road. Average density on the snow road was 0.53 grams per cu cm immediately after construction. Rammsonde hardness number (based on at least 18 measurements) was 68 at first, indicating inadequate hardness. Readings increased to 105 after 17 hours of age hardening, 144 after 25 hours, and 251 after 42 hours, but decreased to 142 after 65 hours.

Successful movement of traffic on a snow road requires a Rammsonde hardness number greater than 350 (Joint Snow Compaction Program 1954). Nevertheless, the snow road was tested with the realization that it would not support intensive traffic. The test road failed during 25 passes of a 3500-kg van with a tire pressure of two atmospheres. The failure of this compacted snow road does not prove or disprove that such roads are in general an acceptable form of winter road. It served, however, to reinforce the conclusion that, unless sufficient moisture is present in the snow, it is impossible to construct a suitable snow road without the use of heavy drags and rollers. Although the snow road could not support intensive traffic it was able to support at least two passes of a 30,000-kg water truck. Sprinkling about 20 litres of water per sq m from the water truck was sufficient to transform the barely-adequate snow road into an ice-capped snow road. Ice-capping of the reconstructed snow road increased its density from 0.50 to 0.63 grams per cu cm, and its average Rammsonde hardness number from 75 to 646, 12 hours after the ice cap was applied. The density of the ice cap was 0.85 grams per cu cm.

The test loop was completed by building up the ice thickness on the other half to obtain a smooth-surface ice road. This required applying about 100 litres of water per sq m. Average density of the ice road remained at 0.89 grams per cu cm throughout its operation. The average thickness of the ice was 13 cm, but it varied over the hummocky terrain of the test site.

A major difficulty was experienced in the use of Rammsonde hardness number and density to indicate whether a winter road is suitable for traffic. In spring, both of these indicators remain at relatively high values after the winter road is no longer offering protection to the vegetation mat. Visual inspection appeared to be a more reliable method of curtailing winter-road use in the spring.

Vehicle speeds ranged from 13 to 24 km per hour for all vehicles during traffic testing. Speed was limited principally by the shortness of length of the straightway and the curves, but also partially by lack of traction. This latter limitation was reduced considerably by light sanding of the ice road.

Elevations of the test loop remained unchanged throughout the tests. No serious wear occurred on either the ice-capped snow road or the ice road. However, after a few days of movement of traffic on the test loop, 33 local fractures occurred on the ice-capped snow road (affecting 2.5% of the road surface) but only one occurred on the ice road. These failures resulted from poor distribution of water during construction, based on Rammsonde hardness. They were repaired with snow and water, and the roads performed well under subsequent traffic movements. No failure was severe enough to prevent continued use of the road. As a result of repairing the ice-capped snow road, the amount of water used to build and maintain it increased from 20 to 34.5 litres per sq m.

By late March the temperatures were high enough for the surface of the ice-capped snow road to melt and puddles to form. This moisture caused the curves to become extremely icy and treacherous.

Some of the later failures on the ice-capped snow road resembled "base failures" common in highway construction where the road base has not been compacted enough. Others resembled typical "scaling failures" on road surfaces due to the freeze-thaw cycle. Cracks formed on both the ice road and ice-capped snow road and much surface melt flowed into and under the road, thereby melting out a "sink-hole" and undermining the road.

During testing with wheeled vehicles, the latter completed almost 36,000 circuits around the 350-m test loop, travelling almost 13,000 km. The vehicles had differing tire pressures and loads (see Tables 1 and 2). Tables 1 and 2 also provide a comparison of the actual test-loop traffic with that estimated for construction of a typical, 130-km-long, pipeline spread (construction segment). The tests described here closely simulated the traffic to be expected during pipeline construction with regard to total number of passes and overall load. Although the maximum individual loads to be expected on a pipeline spread were not reached, the tests did subject the roads to higher tandem-axle loads and tire pressures than could be expected on a spread.

After the wheeled-vehicle tests were completed, the temperature dropped sufficiently to allow the testing of tracked vehicles on the road surface. The ice cap on the ice-capped snow road shattered after 10 passes of the bulldozer; the fragments wore down to smaller pieces after 20 passes, and were reduced to fine consistency after 30 passes. After 100 passes, however, the ice-capped snow road had still not been penetrated completely.

On the ice road, the ice shattered into large pieces after two passes and was well ground into small chips after 10 passes. Penetration to the vegetation mat occurred at one place after 22 passes. After 50 passes, the ice had been turned into fine-textured snow. After 100 passes, only two areas of slight disturbance of the vegetation mat were noted. Several tree stumps in both tracks were badly shredded, but they seemed to have protected the ground surface from damage.

No noticeable scars due to traffic were found during the summer sampling of the test loop, except for a dark strip resulting from an oil leak from the bulldozer. Since turning did not form part of the testing of the tracked vehicles, it is difficult

TABLE 1. Comparison of frequency of passes for a range of tire pressures of vehicles tested on the Norman Wells winter-road loop with those expected on a typical pipeline spread.

	Actual test-loop passes		Expected typical pipeline-spread passes	
Tire pressure (atmospheres)	Number	Relative frequency	Number	Relative frequency
0—0.68	0	0.000	967	0.034
0.69—1.36	0	0.000	19,460	0.685
1.37—2.04	9,473	0.264	460	0.016
2.05—2.72	2,901	0.081	3,702	0.130
2.73—3.40	2,530	0.070	3,470	0.123
3.41—4.08	0	0.000	346	0.012
4.09—4.76	4,731	0.132	0	0.000
4.77—5.44	3,587	0.100	0	0.000
5.45—6.12	12,702	0.353	0	0.000
6.13—6.80	0	0.000	0	0.000
TOTALS	35,924	1.000	28,385	1.000

TABLE 2. Comparison of frequency of passes for various load ranges tested on the Norman Wells winter-road loop with those expected on a typical pipeline spread.

	Actual test-loop passes		Expected typical pipeline-spread passes	
Load range (10^3 kg)**	Number	Aggregated load* (10^7 kg)**	Average number	Aggregated load* (10^7 kg)**
0— 9.1	16,945	7.69	16,551	7.51
9.2—18.1	18,036	24.71	6,400	8.77
18.2—27.2	943	2.14	455	1.03
27.3—36.3	0		4,060	12.91
36.4—45.4	0		24	0.10
45.5—54.4	0		318	1.59
TOTALS	35,924	34.54	28,385	31.09

*Aggregated load = median load range × number of passes
**9.1 × 10^3 kg = 10 tons approx.

to assess the effects of turns of such vehicles. Ice-capped snow roads, however, should respond better than ice roads to turns by tracked vehicles.

Effects on vegetation

No obvious differences in appearance or plant cover could be detected between the half of the test loop used as an ice-capped snow road and the half used as an ice road. The test loop generally had about 12% live-plant cover in late July 1973 (see Table 3), in contrast to almost 50% on adjacent areas which had only been cleared but not used for road construction or otherwise further disturbed. The increase in levels of disturbance from clearing to traffic testing is reflected in the decrease in live-plant cover, and the abundance and composition of individual species. The ground cover on disturbed sites consisted of dead moss and

TABLE 3. Differences in plant cover, thaw depth and peat depth in a black spruce-tamarack-bearberry-moss community in the first summer following the construction and trials of the Norman Wells test site. Data are given as mean values ± standard error.

	Nature of surface						
	Undisturbed	Hand cleared	Machine cleared	Ice road	Snow road	Slash burn area	Seismic line
Percentage plant cover							
Sample size	40	40	40	90	55	27	20
Trees							
Larix laricina	20.5±2.2	3.0±0.7	4.3±0.9	0	0	0	0
Picea mariana	20.3±2.3	3.1±0.6	1.3±0.6	0	0	0	0
Upright shrubs							
Betula glandulosa	3.3±0.5	4.9±0.6	3.0±0.6	1.6±0.2	0.6±0.2	0	3.5±1.0
Ledum groenlandicum	9.1±0.8	6.2±0.8	6.0±0.7	1.3±0.2	1.1±0.2	+	1.9±0.5
Potentilla fruticosa	4.8±0.7	3.5±0.5	6.3±0.7	2.1±0.2	1.5±0.2	0.7±0.2	3.1±0.5
Rosa acicularis	1.4±0.3	2.5±0.3	1.0±0.2	0.3±0.1	0.5±0.2	0.3±0.1	+
Salix spp.	3.6±0.5	3.1±0.6	2.4±0.4	2.0±0.3	1.3±0.3	0.8±0.2	3.2±1.0
Shepherdia canadensis	2.2±0.4	2.7±0.5	3.2±0.8	0.2±0.1	0	0	0
Vaccinium uliginosum	3.2±0.5	0.9±0.3	1.0±0.4	0.5±0.1	0.3±0.1	+	+
Low and prostrate shrubs							
Andromeda polifolia	5.4±0.8	1.1±0.3	1.7±0.3	+	+	0	0.9±0.3
Arctostaphylos rubra	21.5±1.6	12.0±0.9	11.0±1.1	3.2±0.3	4.2±0.5	0.4±0.1	4.7±0.9
Vaccinium vitis-idaea	2.9±0.7	0.7±0.2	0.5±0.3	+	0	0	+
Dryas integrifolia	2.4±0.8	0	0	0	0	0	0
Herbs							
Anemone parviflora	0.5±0.1	0.6±0.1	0.2±0.1	0.2±0.1	0.2±0.1	+	1.1±0.2
Calamagrostis canadensis	0.8±0.2	0.3±0.1	0.4±0.1	0.3±0.1	0.2±0.1	0.4±0.1	0.3±0.1
Carex vaginata	0.6±0.1	0.8±0.1	0.9±0.2	0.3±0.1	0.9±0.1	0	2.0±0.5
Eriophorum vaginatum	1.3±0.3	+	0	0	+	0	0
Saussurea angustifolia	+	0	0	+	0	0	0.7±0.5
Equisetum arvense	2.6±0.5	0.7±0.1	1.7±0.3	0.3±0.1	+	0.4±0.1	1.4±0.4
E. scirpoides	5.9±0.7	2.6±0.2	0.4±0.1	+	+	+	1.6±0.3
Lichens	2.1±1.0	1.2±0.7	0	0	0	0	0
Live mosses	82.4±1.3	0	0	0	0	+	0
Total live plants	197	50	45	12	11	3	25
Litter	16.0±1.1	23.5±2.4	39.8±3.5	24.1±1.4	30.6±2.7	0	8.7±0.7
Dead mosses/Bare peat	0	85.5±2.7	87.1±1.1	92.9±0.5	93.4±0.5	98.0±0.6	89.2±1.5
Depth of thaw (cm)	37.5±0.6	44.1±1.0	59.0±1.9	58.6±0.8	63.1±1.7	64.1±1.9	83.4±3.5
Sample size	80	80	80	180	110	54	40
Depth of peat (cm)	33.1±1.4	35.8±1.0	33.4±2.6	32.3±1.4	32.4±1.0	15.5±0.7	15.5±1.8
Sample size	18	15	12	9	8	11	16

+Signifies a mean cover of less than 0.02%

TABLE 4. Differences in plant cover and thaw depth in a black spruce-tamarack-bearberry-moss community in the first two summers following the construction and trials of the Norman Wells test site. Data are given as mean values ± standard error.

	Nature of surface								
		Ice-capped snow road		Ice road*					
				North half		South half		Seismic line	
	Undisturbed 1973	1973	1974	1973	1974	1973	1974	1973	1974
Percentage plant cover									
Sample size	40	20	16	20	16	20	16	20	16
Trees									
Picea mariana	20.3±2.3	0	0	0	0	0	+	0	0
Larix laricina	20.5±2.2	0	0	0	0	0	0	0	0
Upright shrubs									
Betula glandulosa	3.3±0.5	+	+	2.9±0.6	4.1±1.4	1.3±0.4	3.3±1.0	3.5±1.0	7.1±1.4
Ledum groenlandicum	9.1±0.8	1.4±0.6	1.8±0.6	1.5±0.3	2.6±0.6	1.4±0.4	0.8±0.4	1.9±0.5	1.6±0.6
Potentilla fruticosa	4.8±0.7	2.0±0.4	4.9±0.7	3.1±0.5	6.1±1.1	2.1±0.5	3.3±0.6	3.1±0.5	6.0±0.8
Rosa acicularis	1.4±0.3	0.4±0.2	0.4±0.2	+	+	0.4±0.2	0.7±0.3	+	0.4±0.2
Salix spp.	3.6±0.5	1.3±0.3	3.1±1.1	1.4±0.4	1.4±0.7	1.3±0.5	4.6±1.5	3.2±1.0	4.8±1.9
Shepherdia canadensis	2.2±0.3	0	0	0.8±0.4	1.1±0.5	0	0	0	0
Vaccinium uliginosum	3.2±0.6	+	+	+	1.1±0.5	0.8±0.3	0.7±0.4	+	+
Low and prostrate shrubs									
Andromeda polifolia	5.5±0.8	+	+	+	+	+	0.5±0.2	0.9±0.3	1.7±0.3
Arctostaphylos rubra	21.5±1.6	5.1±0.9	7.9±1.0	4.0±0.6	9.6±1.6	2.4±0.5	5.6±0.7	4.7±0.9	5.6±1.1
Vaccinium vitis-idaea	2.9±0.7	0	0	+	0	+	0	+	0
Dryas integrifolia	2.4±0.8	0	0	0	0	0	0	0	0
Herbs									
Anemone parviflora	0.5±0.1	0.4±0.1	0.9±0.3	0.4±0.2	+	+	0.6±0.2	1.1±0.2	3.6±0.9
Calamagrostis canadensis	0.8±0.2	0.4±0.1	1.1±0.4	0.6±0.1	2.3±0.5	0.4±0.2	0.8±0.4	0.3±0.1	2.1±0.5
Arctagrostis latifolia	+	+	+	+	+	+	+	+	+
Carex vaginata	0.6±0.1	1.0±0.2	2.1±0.4	+	0	0.3±0.1	0.5±0.2	2.0±0.5	5.2±1.3
C. aquatilis	+	0	0	+	0.8±0.4	0	0	0	0
Eriophorum vaginatum	1.3±0.3	0	1.4±0.2	0	0	0	+	0	1.4±0.2
Saussurea angustifolia	0	0	0	0	0	0	0	0.7±0.5	0.9±0.5
Gentiana propinqua	0	0	0	0	0	0	+	+	+
Parnassia palustris	0	0	0	0	+	0	0	0	+
Equisetum arvense	2.6±0.5	+	1.6±0.3	1.3±0.3	6.3±1.1	0	0.5±0.2	1.3±0.4	1.0±0.3
E. scirpoides	5.9±1.3	+	3.3±0.3	+	2.7±0.5	+	4.3±0.6	1.6±0.3	2.9±0.6
Lichens	2.2±1.0	0	+	0	0	0	0	0	0
Live mosses	82.4±1.3	0	2.5±0.6	0	4.7±1.3	0	9.4±1.7	0	2.2±0.6
Total live plants	198.1±4.5	12.3±1.2	31.6±2.3	16.8±1.9	44.4±5.0	11.0±1.3	35.6±3.5	24.6±2.1	46.9±2.9
Litter	16.0±1.1	32.5±5.1	33.8±5.0	19.3±2.7	17.8±3.0	13.3±2.1	12.2±1.5	8.7±0.7	8.8±0.6
Dead moss/Bare peat	0	94.8±0.8	91.9±0.8	93.5±1.2	91.3±2.4	96.5±0.8	87.2±1.9	89.2±1.5	87.8±2.2
Depth of thaw (cm)									
Sample size	80	40	32	40	32	40	32	40	32
1973	37.5±0.6	62.4±2.4		66.9±1.8		49.4±0.9		82.4±3.5	
1974	47.5±1.1		75.6±2.1		79.9±1.8		61.5±1.3		81.9±2.0

*The north half of the ice road contained some standing water and was wetter than the south half in 1974. No such differences were seen in 1973.
+Signifies a mean cover of less than 0.3%

bare peat, since exposure to light killed the feathermosses. The fact that seedlings of tamarack and black spruce were not eliminated in the process of site clearance accounted for the presence of these species on cleared areas but their virtual absence from the test loop. Most shrub species were generally taller and more abundant on cleared areas than on the test loop.

By 1974, live-plant cover had more than doubled on the test loop (see Table 4). On the transects sampled on 20-23 July 1973 and 8 August 1974, live-plant cover had increased from 11-16% in 1973 to 31-44% in 1974. Live mosses were absent in 1973 but appeared in 1974. Most of the low plant cover in 1973 was of shrubs and herbs which sprouted from viable root-stocks or rhizomes. The area covered by individual surviving clumps was greater in 1974, and the shrubs were generally taller than in the previous year. ***Arctostaphylos rubra*** was the principal heath plant to recover, for it is one of the fastest-increasing species, as has been observed after other disturbances during which the overstory was cleared but the rooting zone was not destroyed (Hernandez 1973). Several grasses, sedges, and herbs are slowly increasing in cover.

A seismic line constructed through the area in October 1971 was sampled for comparison with the test loop in both 1973 and 1974 (Table 4). Live-plant cover almost doubled from 25% to 47%, as the size of surviving clumps of most species is gradually expanding. Some new species had also become established on the seismic line, probably from seed. This pattern of recovery is similar to that for other seismic lines (in the Mackenzie Delta) where plant cover increased from 1.4% in the first summer after disturbance to 21% in the second and 67% by the third summer (Hernandez 1973). Most plant cover noted in that study and the present one was the result of resprouting from surviving root-stocks, but new species began to seed in by the second and third years. The test loop, as expected, appears to be following this pattern (see Table 4). In general, these results indicate that properly constructed and maintained winter roads on flat and gently-sloping areas of the boreal forest have similar effects on vegetation as seismic lines.

Two additional experiments were incorporated into the test programme: to compare the effectiveness of machine-, as opposed to hand-, clearing, and to determine the effects of burning "slash" (cleared woody debris) directly on the snow (see Table 3).

Hand-cleared areas had generally slightly greater live-plant cover, taller shrubs, and less litter than the machine-cleared area. Mosses, though dead, were otherwise not disturbed on the hand-cleared areas, whereas on the machine-cleared area, the imprint of the bulldozer tracks was clearly visible where the mosses were compressed. In addition, small patches (about 0.25 sq m) of moss were disturbed and mineral soil exposed throughout the machine-cleared area. These patches only represented about 0.1% of the cleared area, however. Most trees broke off cleanly, only about 4% of them being uprooted. About 70% of those uprooted were 7-15 cm in diameter. (Density of trees greater than 3 cm in diameter at breast height was 0.3 per sq m.)

Although land cleared by hand has a neater appearance and less compaction and is subject to smaller increases in thaw depth than land cleared by machine, clearing an area by hand takes much longer, and its advantages are lost if the area is to be subjected to additional disturbances.

The areas where the slash was burned on the snow and frozen ground were the most severely disturbed. Total live-plant cover was only 3% in 1973 (see Table 2) and only a little greater in 1974. Ground cover was 98% burned peat. What initially appeared to be a settlement of 10-20 cm in these areas was, in fact, the result of the burning of the surface peat. Depth of peat, which was 32-35 cm on all other areas of the test loop and the cleared areas, was only 15 cm on the areas of burning (see Table 3). These results indicate that burning of slash directly on the ground is completely unacceptable, especially on ice-rich permafrost areas, because the insulating surface peat is also burned off.

Effects on peat and depth of thaw

Removing the forest canopy alone increases soil temperatures and thaw depth, if only as a result of the change from a three- to a two-dimensional energy absorbing system (Haag and Bliss 1974a). In contrast, in the tundra, peat depth is the factor which controls thaw depth and ground temperatures (Haag and Bliss 1974b). Disturbance, however, generally does more than remove the forest canopy; the ground layer is disturbed, compacted, or churned, depending on the intensity of disturbance and time of year. These activities compact the peat, thereby increasing its bulk density and thermal conductivity, and in consequence depth of thaw is increased even more. The effects of these interrelated factors, of intensity of disturbance and time of year, on compaction, bulk density and depth of thaw, on different areas of the test site, are set out in Table 5. Construction and use of winter roads resulted in a slightly greater compaction of peat and a deeper thaw than did the removal of vegetation by machine. The differences, however, are not as great as those which arise during the summer when levels of activity are much lower. The data obtained from sampling the seismic line which bisects the test loop support this fact.

TABLE 5. Thaw depth and bulk density of peat samples taken from various areas of the Norman Wells test site.

Treatment	Bulk density: Mean ± standard error (grams per cc)	Bulk density: Size of sample	Bulk density: Range (grams per cc)	Thaw depth (from Table 3): Mean ± standard error (cm)	Thaw depth (from Table 3): Size of sample
Undisturbed	0.0750 ± 0.0079	9	0.039-0.109	37.5 ± 0.6	80
Hand cleared	0.0471 ± 0.0023	5	0.042-0.054	44.1 ± 1.0	80
Machine cleared	0.0882 ± 0.0112	5	0.063-0.123	59.0 ± 1.9	80
Ice road	0.0941 ± 0.0166	13	0.047-0.207	58.6 ± 0.8	180
Ice-capped snow road	0.0977 ± 0.0079	8	0.073-0.121	63.1 ± 1.7	110
Seismic line: shoulder	0.1922 ± 0.0645	5	0.109-0.331	82.4 ± 3.5	40
: trail	0.2769 ± 0.0396	5	0.198-0.391		

The seismic line dates from October 1971. It was used as an access footpath to other nearby areas of study in the summers of 1972 and 1973. Foot traffic wandered over much of the line but was more common along a trail which was depressed 10-20 cm by 1973. Average foot traffic over the line was four man passes per day for four months in the summer of 1972, and two man passes per day for two months before sampling in July 1973. This represents a total of about 600 man passes and is equivalent to an aggregated load of about 4.5 x 10^4 kg. Depth of thaw was greatest (over 90 cm) on the depressed trail, where only a few measurements were taken, and on the edge of the seismic line. Bulk density was similarly 270% greater on the footpath than on undisturbed surfaces, and 160% greater on the shoulder of the seismic line. In contrast, winter passage of 3.5 x 10^8 kg in aggregate on the vehicle loop caused bulk density to increase by only 25-30%. Mackay (1970) similarly points out the vulnerability of permafrost terrain to light summer disturbance by describing the effects of a dog chained for 10 days at one spot. Haag and Bliss (1974b) report a four-fold increase in bulk density (from 0.17 to 0.69 grams per cu cm) on a snow trail used to supply a dynamite storage shack for several years, and along which some summer low-ground-pressure vehicular traffic passed.

The foregoing results serve to indicate the sensitivity of the terrain to disturbance in summer and its tolerance of much greater activity in winter, especially if care is taken to properly construct and maintain winter roads.

DISCUSSION

Winter road use: implications for pipeline construction

Because Canadian Arctic Gas Pipeline Limited and Foothills Pipe Lines Ltd. propose to rely on winter roads as a means of reducing damage to vegetation and permafrost during pipeline construction in northern areas (C.A.G.P.L. 1974a; Foothills 1975), the limitations of the tests reported in this paper, the limitations of other tests and the difficulties which could arise must be considered. From the present study, tests carried out at Inuvik in 1973-74 (C.A.G.P.L. 1974b) and the experiences of companies exploring for oil on the Tuktoyaktuk Peninsula (Hernandez 1973), it has been shown that winter snow and ice roads *can* be used to greatly reduce compaction and destruction of peat in such areas, even on gradients of up to about 6° (12%) and on similar sideslopes, *if* such roads are properly constructed and maintained and their use stopped before spring melt commences.

On the Yukon coast, however, winter roads may not be as effective in protecting the permafrost, largely because of the high ice content of the soils there. A winter snow road was used twice — to move a drilling rig in, and to take the rig out — near the Blow River (Kerfoot 1972). The ponding which started in 1971 (Kerfoot 1972) was still visible and virtually continuous along the entire road in 1974, and will probably continue for several years. Construction, maintenance, and use of winter roads in this area will probably have to be more stringently controlled than those in all other areas to be crossed.

The possibility of using proper winter roads for pipeline construction will depend upon snow falling in sufficient quantity for them to be prepared before actual construction begins. Adam (1974) has examined the limitations which season and climate place upon the construction and use of snow roads. A shortage of snow combined with a reduction in length of season available for snow-road construction can be expected about one year in five — at least from Inuvik to the south. Such conditions occurred in 1973 when the Inuvik winter-road tests were carried out (C.A.G.P.L. 1974b). Snow for construction of the test loop had to be hauled in on an existing gravel road from a nearby lake and some also manufactured. About 7500 cu m of snow were required to construct the 800-m-long test loop (C.A.G.P.L. 1974b). Snow on the lake was at most about 15 cm deep (Atmospheric Environment Service 1974). Assuming that the snow density was about half of the 0.60 grams per cu cm required for usable roads (Adam 1973b), and allowing for the presence of some snow on the ground, one may conclude that an area of the order of 0.16 sq km of snow source would be required per linear kilometre of road. Although snow hauling may be allowed for in case of necessity, it needs to be remembered that access roads to the sources of snow would also have to be properly constructed and maintained winter roads, if unnecessary damage to vegetation and underlying permafrost is to be avoided.

Snow manufacturing, ice-capping, but especially ice-road construction all require large volumes of water which would have to come from nearby rivers, springs, or lakes. In winter, flows and oxygen levels are normally low in northern streams, and lakes and springs are important overwintering sites for fish. The effects on these aquatic ecosystems of removing the required large volumes of water at this time will also have to be considered before reliance can be placed on their availability as sources of water for winter-road construction.

CONCLUSIONS

Winter roads are an effective means of reducing damage to vegetation and permafrost in the Mackenzie Valley and along the east side of the Mackenzie Delta. Properly constructed and maintained, such roads can withstand the volumes and loads of traffic associated with pipeline construction. It cannot be stressed enough, however, that the benefits gained by using winter roads are lost if the roads are built too early in the fall, used too late into the spring, or otherwise put into service without careful construction and provision for regular maintenance.

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