A MODEL FOR MAPPING PERMAFROST DISTRIBUTION BASED ON LANDSCAPE COMPONENT MAPS AND CLIMATIC VARIABLES

M.T. Jorgenson[1] and R.A. Kreig[2]

[1]Alaska Biological Research, Inc., Fairbanks, Alaska
[2]R.A. Kreig and Associates, Inc., Anchorage, Alaska

SYNOPSIS

A computer model for mapping permafrost distribution was developed that uses vegetation, terrain unit and equivalent latitude maps and regional air temperature data as the geographic data base for calculating the heat balance of the ground surface. The ratio of the amount of heat entering the soil in the summer, when the ground was seasonally thawed, and lost during the winter, when the ground was seasonally frozen, was calculated from the degree-day sums at the surface and soil thermal conductivities. Thermal parameters used in the computations were assigned to the vegetation and terrain unit types and modified by the equivalent latitude map. The simulated permafrost distribution within the Spinach Creek Watershed near Fairbanks, Alaska, agreed closely with the distribution mapped by photointerpretation. The effects of climatic warming on permafrost distribution were also assessed. Within the mapping area, permafrost covered 100% of the area below a mean annual air temperature of -7.7°C, 37.3% at -3.5°C, 21.3% at 0°C and was eliminated above 2.6°C.

INTRODUCTION

Recent efforts to develop models for predicting permafrost distribution have emphasized the relationships between permafrost and vegetation, soil, topography, air temperature and snowcover. A site-specific approach using digital terrain data, developed by Morrisey (1986), integrated vegetation, topography and thermal imagery. Nelson (1986) developed a computational method for the regional mapping of permafrost distribution based on minimal climatic data and subsurface information. The model presented in this paper uses both landscape component maps, delineating vegetation, terrain units, and equivalent latitude values, and regional climatic data for site-specific large scale mapping of permafrost. This approach allows the model to be responsive to the spatial variability of a landscape and to changes in climate.

An essential prerequisite for permafrost distribution models is the simplification of surface heat balance computations in order to reduce the number of site-specific variables needed in the geographic data base. Energy budget models (Goodwin and Outcalt 1975, Ng and Miller 1977) that utilize a large number of radiative, thermal and aerodynamic parameters of the surface, more realistically account for the pathways involved in establishing the heat balance at the surface, but are not feasible for regional mapping methodologies. More appropriate to regional mapping models are simpler approaches that relate soil temperature or soil heat flux to air temperature (Lunardini 1978, Haugen et al. 1983), net radiation (Abbey et al. 1978), and to biophysical factors of the surface (Jorgenson 1986).

Large-scale permafrost mapping models must also be able to incorporate remote sensing products that identify and classify characteristics of the landscape that have differing microclimatic and soil thermal properties. Much progress has been made in classifying and characterizing the vegetation (Viereck et al. 1983) and terrain unit (Kreig and Reger 1982) components of the landscape through the use of remotely sensed data, including satellite imagery and aerial photography. However, the weakest area for model development is the limited data base characterizing the microclimates of a broad range of vegetation types and analyses that account for the geographic variability of soil temperature.

A portion of the Spinach Creek Watershed, located 25 km NW of Fairbanks, Alaska, was selected as the test site for model development. This mountainous watershed is representative of much of the Yukon-Tanana uplands. The slopes have a shallow mantle of loess or have shallow residual soils on steeper sites. The valley bottom is generally filled with fine-grained retransported deposits removed from the hillsides. Closed stands of aspen, birch, and white spruce predominate on upland slopes, facing east, south and west. The valley bottom, ridge tops and north-facing slopes are dominated by black spruce. In valley bottoms, tussock bogs occur in small patches and low shrubs occur along small creeks and drainages.

STRUCTURE AND THEORETICAL BASIS FOR MODEL

The model uses the simple relationship offered by Carlson (1952) as the approximate criteria for permafrost formation. For any particular site, the ratio of the annual amount of heat

SYNOPSIS

A computer model for mapping permafrost distribution was developed that uses vegetation, terrain unit and equivalent latitude maps and regional air temperature data as the geographic data base for calculating the heat balance of the ground surface. The ratio of the amount of heat entering the soil in the summer, when the ground was seasonally thawed, and lost during the winter, when the ground was seasonally frozen, was calculated from the degree-day sums at the surface and soil thermal conductivities. Thermal parameters used in the computations were assigned to the vegetation and terrain unit types and modified by the equivalent latitude map.

The simulated permafrost distribution within the Spinach Creek Watershed near Fairbanks, Alaska, agreed closely with the distribution mapped by photointerpretation. The effects of climatic warming on permafrost distribution were also assessed. Within the mapping area, permafrost covered 100% of the area below a mean annual air temperature of -7.7°C, 37.3% at-3.5°C, 21.3% at 0°C and was eliminated above 2.6°C.

INTRODUCTION

Recent efforts to develop models for predicting permafrost distribution have emphasized the relationships between permafrost and vegetation, soil, topography, air temperature and snowcover. A site-specific approach using digital terrain data, developed by Morrisey (1986), integrated vegetation, topography and thermal imagery. Nelson (1986) developed a computational method for the regional mapping of permafrost distribution based on minimal climatic data and subsurface information. The model presented in this paper uses both landscape component maps, delineating vegetation, terrain units, and equivalent latitude values, and regional climatic data for site-specific large scale mapping of permafrost. This approach allows the model to be responsive to the spatial variability of a landscape and to changes in climate.

An essential prerequisite for permafrost distribution models is the simplification of surface heat balance computations in order to reduce the number of site-specific variables needed in the geographic data base. Energy budget models (Goodwin and Outcalt 1975, Ng and Miller 1977) that utilize a large number of radiative, thermal and aerodynamic parameters of the surface, more realistically account for the pathways involved in establishing the heat balance at the surface, but are not feasible for regional mapping methodologies. More appropriate to regional mapping models are simpler approaches that relate soil temperature or soil heat flux to air temperature (Lunardini 1978, Haugen et al. 1983), net radiation (Abbey et al. 1978), and to biophysical factors of the surface (Jorgenson 1986).

Large-scale permafrost mapping models must also be able to incorporate remote sensing products that identify and classify characteristics of the landscape that have differing microclimatic and soil thermal properties. Much progress has been made in classifying and characterizing the vegetation (Viereck et al. 1983) and terrain unit (Kreig and Reger 1982) components of the landscape through the use of remotely sensed data, including satellite imagery and aerial photography. However, the weakest area for model development is the limited data base characterizing the microclimates of a broad range of vegetation types and analyses that account for the geographic variability of soil temperature.

A portion of the Spinach Creek Watershed, located 25 km NW of Fairbanks, Alaska, was selected as the test site for model development. This mountainous watershed is representative of much of the Yukon-Tanana uplands. The slopes have a shallow mantle of loess or have shallow residual soils on steeper sites. The valley bottom is generally filled with fine-grained retransported deposits removed from the hillsides. Closed stands of aspen, birch, and white spruce predominate on upland slopes, facing east, south and west. The valley bottom, ridge tops and north-facing slopes are dominated by black spruce. In valley bottoms, tussock bogs occur in small patches and low shrubs occur along small creeks and drainages.

STRUCTURE AND THEORETICAL BASIS FOR MODEL

The model uses the simple relationship offered by Carlson (1952) as the approximate criteria for permafrost formation. For any particular site, the ratio of the annual amount of heat entering the soil compared to the amount leaving (R), is dependent on the temperature degree-days sums at the surface and the thermal conductivities of the soil when it is thawed or frozen:

$$R = (DDT_s/DDF_s)/(K_f/K_t) \qquad (1)$$

where DDT_s and DDF_s are surface thawing and freezing indices based on degree-day sums and K_f and K_t are the thermal conductivities of frozen and thawed soil.

The freezing and thawing degree-day sums and the frozen and unfrozen thermal conductivities of the soil are considered the most important variables. The use of n-factors (Lunardini 1978) and regional climatic data provided the simplest way to estimate surface temperature, which is a function of the total heat transfer at the surface. On the other side of the equation, the importance of the ratio of frozen to unfrozen thermal conductivities to permafrost formation has long been recognized for organic soil horizons and is of equal significance for mineral soils. The rate at which heat is lost from fine- and coarse-grained soils relative to the rate at which heat enters the profile increases rapidly with increasing moisture content of the soil (Fig. 1, Kersten 1949). This makes wet mineral soils, such as those fine-grained deposits in valley bottoms and depressions, particularly susceptible to permafrost formation. The frozen/unfrozen conductivity ratio is even higher for saturated organics approaching that of water, about 4 (Farouki 1981). However, at very low moisture contents the conductivity of frozen soil is less than that of unfrozen soil presumably because freezing reduces some of the bridge water between particles. This makes drier sites, such as well-drained soils beneath aspen stands, less susceptible to permafrost formation.

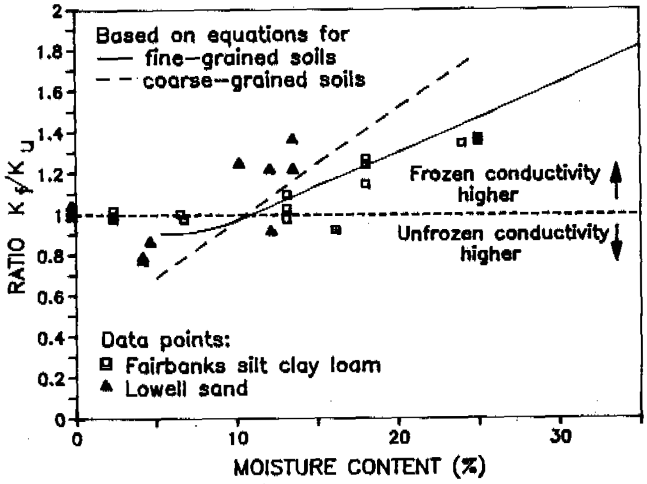

Figure 1. Effects of soil moisture on the ratio of frozen (K_f) to unfrozen (K_u) thermal conductivities. Ratios of equations (5)/(4) and (7)/(6) are plotted (see text). Data and equations are from Kersten (1949).

Surface temperatures are related to air temperatures using n-factors in the following equation:

$$R = ((DDT_a\ N_t\ P)/(DDF_a\ N_f))/(K_f/K_t) \qquad (2)$$

where DDT_a is the thawing degree-days and DDF_a is the freezing degree-days of the air (above 0^oC) and N_t and N_f are thawing and freezing n-factors. P is a potential insolation index that modifies the summer n-factor according to the position on the landscape and is calculated by:

$$P = L/L_e, \qquad (3)$$

where L is the latitude and L_e is the equivalent latitude of the site. The effect is to increase the n-factor on warmer sites and reduce the n-factor on colder sites.

Kersten's (1949) empirical equations were used to calculate the thermal conductivities of frozen and unfrozen soils. The equations give the thermal conductivity (K) of the soil in terms of its moisture content w (%) and its dry density γ_d. For unfrozen fine-grained soils

$$K_t = 0.1442(0.9\log w-0.2)10^{0.6243\gamma_d} \qquad (4)$$

and for frozen fine-grained soils

$$K_f = 0.001442(10)^{1.373\gamma_d} + 0.01226(10)^{0.4994\gamma_d}{}_w. \qquad (5)$$

For unfrozen coarse-grained soils

$$K_t = 0.1442(0.7\log w + 0.4)10^{0.6243\gamma_d} \qquad (6)$$

and for frozen coarse-grained soils

$$K_f = 0.01096(10)^{0.8116\gamma_d} + 0.00461(10)^{0.9115\gamma_d}{}_w. \qquad (7)$$

The water content of the soil was modified by the equivalent latitude of the site using:

$$w = w_m\ (L/L_e), \qquad (8)$$

where w_m is the typical soil moisture for a given vegetation type. This has the effect of reducing soil moisture on south-facing sites and increasing moisture on north-facing sites.

Although the effects of snow cover on winter soil temperatures, and thus permafrost distribution, were recognized as important factors, snow depth and density were not directly incorporated into the model. Difficulties in mapping snow cover distribution precluded the use of snow effects in the model. Instead, the snow cover effects are inherent in the winter n-factors associated with each vegetation type.

MODEL INPUTS

Permafrost is mapped by calculating the heat balance at the ground surface for each pixel (picture element) of the mapping area. The FORTRAN program reads the vegetation, terrain unit and equivalent latitude map files, in raster format, and assigns landscape component classes to each pixel. Thermal parameters char-

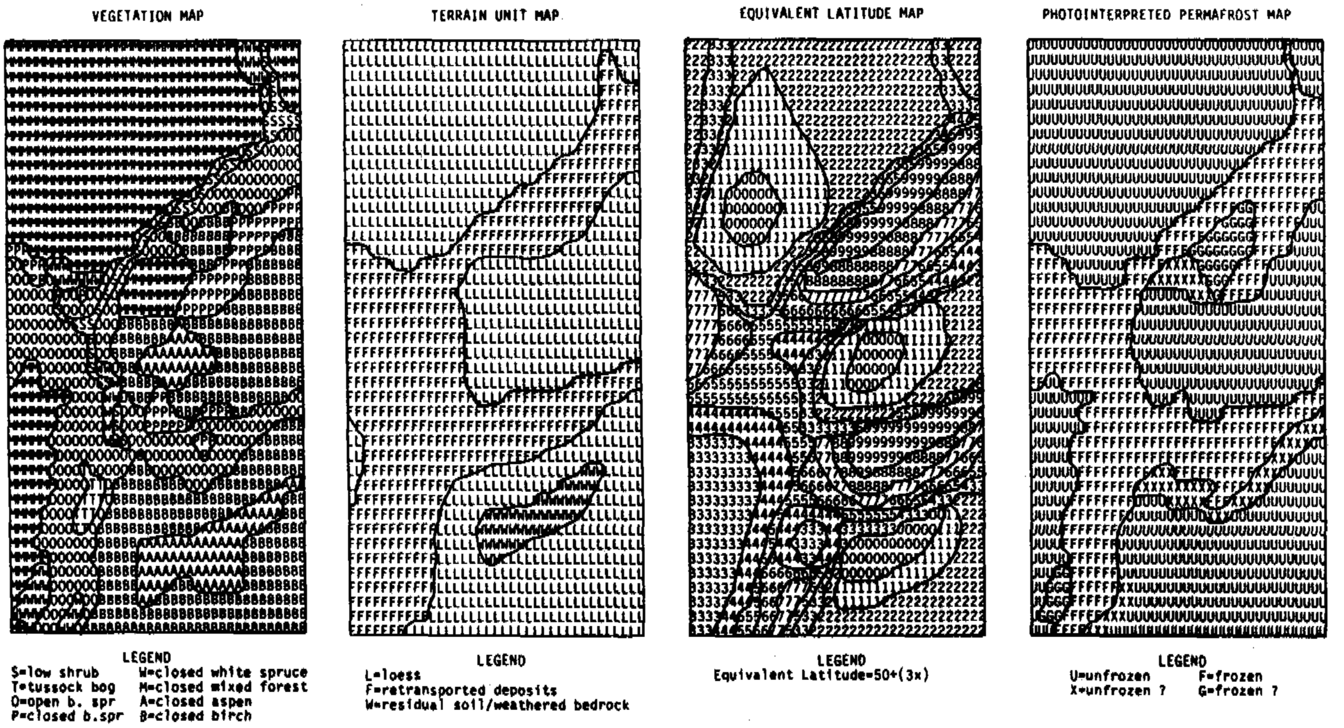

Figure 2. Landscape component maps for a portion of the Spinach Creek Watershed, Fairbanks, Alaska.

acteristic of each landscape component class were then assigned to each pixel for the heat balance computation, depending on the class assigned to each pixel. Summer and winter n-factors and soil moisture values assigned to each vegetation type are presented in Table I. The bulk densities assigned to each terrain unit were; 1.30 g/cm^3 for loess, 1.20 for retransported deposits, and 1.60 for residual soils. Thus, the frozen and unfrozen thermal conductivities of each pixel are a function of soil moisture values characteristic of each vegetation type and bulk densities characteristic of each terrain unit. A thawing degree-day value (°C) of 1700 and a freezing degree-day value of 2950 were used for the Fairbanks long-term air temperature annual sums.

Table I. Thermal parameters assigned to each vegetation type.

Vegetation type	N-factor N_t	N-factor N_f	Soil Moisture (% wt.)
Closed aspen forest	1.00	0.30	15
Closed birch forest	0.90	0.35	20
Mixed birch-spruce forest	0.85	0.35	20
Closed white spruce forest	0.80	0.35	50
Open black spruce forest	0.60	0.30	50
Closed black spruce forest	0.50	0.30	45
Low shrub scrub	0.85	0.30	40
Tussock bog	0.90	0.30	55

The model was applied to a data base incorporating vegetation, terrain unit and equivalent latitude maps. The vegetation and terrain unit maps were delineated from airphotos (1:63,000 CIR) for a portion (1.6 x 3.0 km) of the Spinach Creek Watershed and then converted to raster format (Fig. 2). The equivalent latitude map was based on a 1:63,000 USGS topographic map using the approach of Dingman and Koutz (1974). Each pixel covers 43 x 74 m on the ground. To assess the validity of the model output, permafrost distribution was also delineated from the airphotos and agreement between methods was compared.

SIMULATION RESULTS

The model was initially run using n-factors developed from air and surface temperature in reports by Linnell (1973), Viereck et al. (1983), and Haugen et al. (1983). The initial run mapped 33.4% of the area as permafrost, similar to the 32.1% mapped by photo-interpretation. However, the photo-interpretation also mapped 2.6% of the area as questionably frozen and 4.4% as questionably unfrozen, thus the percentage of frozen area ranged from 25.1% to 39.1% when the uncertain areas were added or deleted. Small adjustments were then made to the thermal parameters of the vegetation types so that several of the north-facing deciduous stands and valley-bottom white spruce stands were mapped in subsequent runs as frozen instead of unfrozen. The transition zones along ridges and toes of slopes also

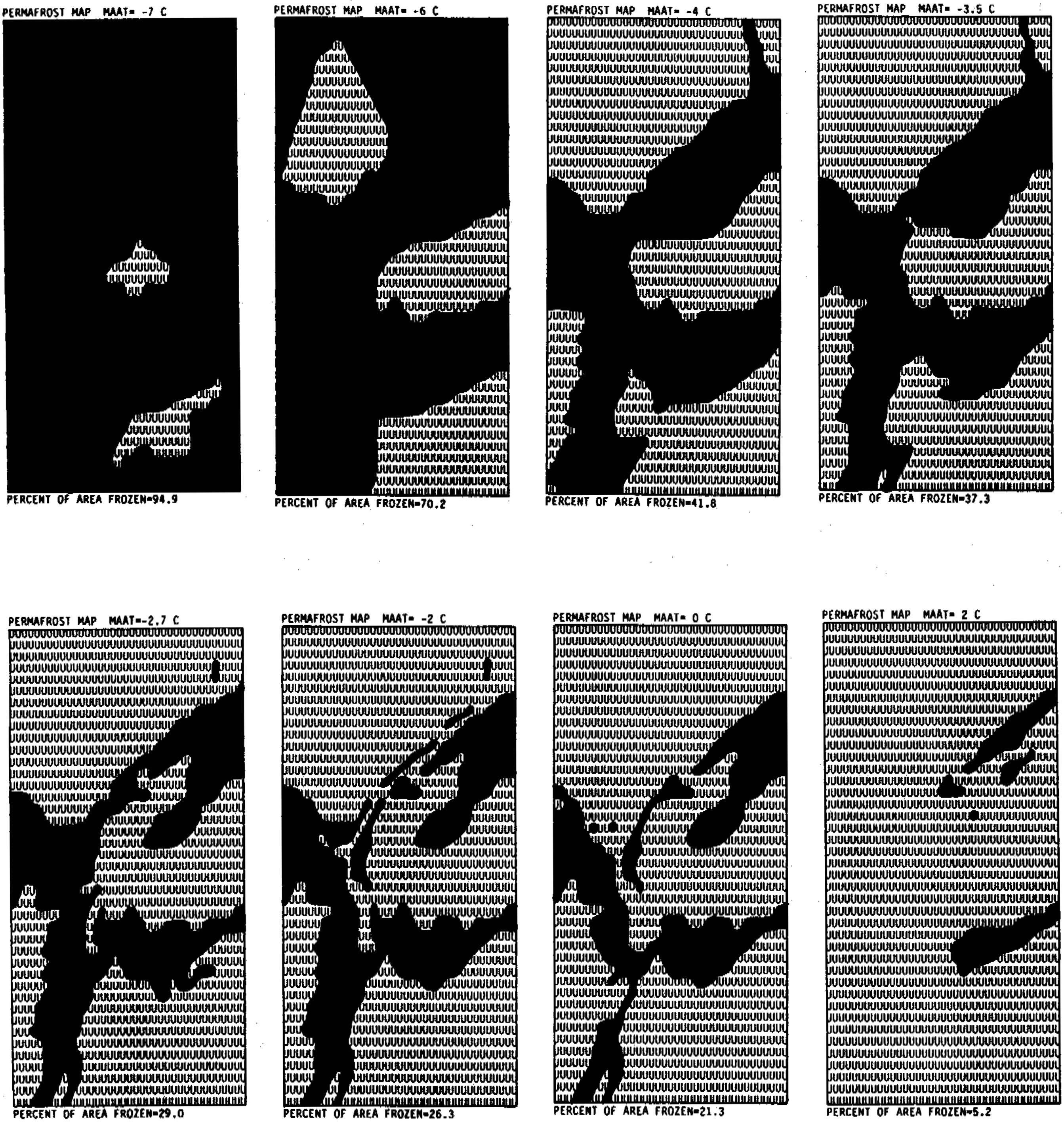

Figure 3. Simulated effects of different mean annual air temperatures on permafrost distribution.

changed slightly. In the final version used for sensitivity analysis, 37.3% of the area was mapped as frozen.

The sensitivity of permafrost distribution to changes in soil moisture and n-factors, parameters which affect the calculation of surface heat balance, were tested. When soil moisture was reduced or increased by 30%, the frozen area covered 26.4% and 45.4% respectively.

N-factors were increased and decreased by 30% in various combinations. When only the thaw n-factors (N_t) were increased and decreased, permafrost coverage varied from 26.0% to 79.2%. When only freeze n-factors (N_f) were changed, the frozen area varied from 25.6% to 53.7%. When N_t was increased and N_f was decreased, the frozen area covered 20.5%. When N_t was decreased and N_f increased, the frozen area covered 94.9%.

The analyses indicated that the model was very sensitive to n-factors but less sensitive to soil moisture variations. Therefore, some uncertainty accompanies the use of n-factors, which by their nature are quite variable from month to month and from year to year even within a given site (Lunardini 1978). However, there was only a limited range that produced a permafrost map similar to the photointerpreted permafrost map.

RESPONSE OF PERMAFROST TO CLIMATIC CHANGE

The model was used to assess the effects of air temperature, and thus climatic change, on permafrost distribution within the Spinach Creek test area (Fig. 3). Permafrost coverage was 100% at a mean annual air temperature (MAAT) below -7.7°C. From -7.7 to -6°C, the warmest south-facing slopes became unfrozen. From -6 to -4°C, east and west portions of midslopes, above the retransported deposits became thawed. From -3.5 to -2.7°C (the difference between the Fairbanks long-term average and 14 year average, 1968-1982), deciduous forests on NE and NW facing slopes and steep south-facing drainages became thawed. Between -2 and 0°C, change was limited to black spruce stands occurring along the lower portions of south-facing slopes. Between 0 and 2°C, all black spruce stands and tussock bogs on retransported deposits in the valley bottoms became thawed. Above 2°C, permafrost persisted only on limited portions of steep north-facing slopes. At 2.6°C, all permafrost was eliminated.

EVALUATION OF MODEL

The validity of the model can be partially evaluated by indirect means. Although no field verification was done on the permafrost map (present climatic conditions), good agreement (92.7%) was achieved between the simulated map (MAAT=-3.5°C) and the photointerpreted map.

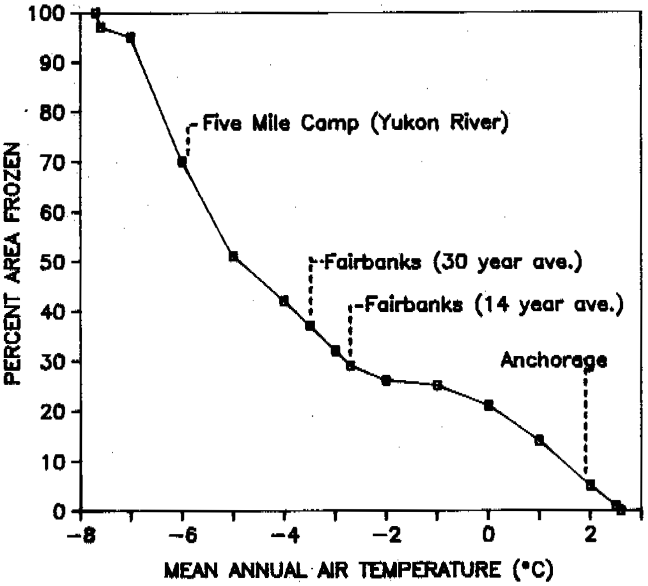

Figure 4. Simulated effects of changes in mean annual air temperatures on the percent of area frozen. Air temperatures at Five Mile Camp and Anchorage are included for comparison.

Good agreement was also found between the results of the temperature effect simulations, in which permafrost became continuous below -7.7°C MAAT and absent above 2.6°C MAAT, and other evidence (Fig. 4). According to Haugen (1982), MAAT's on the south side of the Brooks Range, where permafrost is discontinuous, ranged from -5.9 to -6.9°C and MAAT's in the Arctic foothills, where permafrost is continuous, ranged from -6.7 to -11.1°C (years 1975 to 1979). Brown (1967) used the -8.3°C MAAT isotherm to delimit the boundary between continuous and discontinuous permafrost and -1.1°C to delimit the boundary between discontinuous and sporadic permafrost. Harris (1981) concluded that the boundary between discontinuous and sporadic permafrost lies just on the cold side of 0°C. In our model, permafrost became sporadic (<25%) in the mapping area at MAAT of -1.0°C. Harris also noted sporadic patches of ice beneath peat have been found at MAAT's as warm as 5°C but were more frequently found at MAAT's below 3°C.

The identification of north-facing slopes as the last locality for permafrost to persist is inconsistent with some observed occurrences, however, and may be due to the lack of groundwater effects in the model. Experience in south-central Alaska and other areas at the southern limit of permafrost indicates that the last pockets of permafrost would normally be expected to occur around the edges of bogs and peatlands that do not receive groundwater discharge from (warmer) higher upland slopes.

CONCLUSIONS

Several conclusions can be drawn from this preliminary effort. The approach appears to work quite well in modelling the natural distribution of permafrost in the Spinach Creek test area. The model is relatively simple and the required inputs are factors that can be mapped by skilled photointerpreters and/or derived from database analyses of soil test data and climatic data. However, it should be noted that modelling (as well as photointerpretive permafrost mapping) can be expected to be easier in hilly terrain, such as the test area, that has 1) relatively thin loess cover, and 2) strong gradients in incident solar radiation. In addition, the role of groundwater is important and cannot be neglected, especially in landscapes that are flatter, have more complex geology and vegetation, and in more maritime climates.

Although this model was run on a specific area near Fairbanks, the results of the mean annual air temperature simulations can be applied to Alaska's Interior in a general way and have implications for human development on permafrost. Relatively little change might be expected to occur from a climatic warming from-3.5 to 0°C, except at transition zones along permafrost boundaries, particularly on retransported deposits on the lower portions of south-facing slopes. Above 0°C, permafrost degradation would accelerate and all valley bottoms, where much infrastructure development occurs, would become thawed. The thawing of remnant permafrost on steep north-facing hills at MAAT's between 2 and 2.5°C would likely have little effect on human use since these sites are rarely developed.

REFERENCES

Abbey, F L, Gray, D M, Male D H, and Erickson, D E L (1978). Index models for predicting ground heat flux to permafrost during thaw conditions, in Proc. 3rd Int. Conf. on Permafrost, Vol. 1, Nat. Res. Coun. Canada. 4-9.

Brown, R J E (1967). Permafrost in Canada. Geol. Surv. of Can. Map 1246A.

Carlson, H (1952). Calculation of depth of thaw in frozen ground, in Frost action in soils. High. Res. Board Spec. Rep. No. 2, 192-223.

Dingman, S L and Koutz, F R (1974). Relations among vegetation, permafrost and potential insolation in central Alaska. Arc. Alp. Res. (6),1,37-42.

Farouki, O T (1981). Thermal properties of soils. U.S. Army Cold Reg. Res. Eng. Lab., Hanover, NH. CRREL Mono. 81-1, 136pp.

Goodwin, C W and Outcalt, S I (1974). The simulation of the geographic sensitivity of active layer modification effects in northern Canada, in Env. Soc. Comm. on North. Pipe., Task For. on Nor. Oil Dev., Rep. 74-12, 17-49.

Harris, S A (1981). Climatic relationships of permafrost zones in areas of low winter snow cover. Arctic (34),1,64-70.

Haugen, R K (1982). Climate of remote areas in north-central Alaska. U.S. Army Cold Reg. Res. Eng. Lab., Hangover, NH, CRREL Rep. 82-35, 110pp.

Jorgenson, M T (1986). Biophysical factors influencing the geographic variability of soil heat flux near Toolik Lake Alaska: implications for terrain sensitivity. Unpub. M.S. Thesis. Univ. of AK. 109pp.

Kersten, M S (1949). Thermal properties of soils, Univ. Minn. Eng. Exp. Sta., Bull. No. 28, 225pp.

Kreig, R A and Reger, R D (1982). Airphoto analysis and summary of landform soil properties along the route of the Trans-Alaska Pipeline System. Ak. Div. Geol. Geoph. Sur., Geol. Rep. 66, 149pp.

Linell, K A (1973). Long term effects of vegetation cover on permafrost stability in an area of discontinuous permafrost, in North Amer., Cont. of 2nd Int. Conf. on Permafrost, Yakutsk, Siberia., 688-693.

Lunardini, V J (1978). Theory of n-factors and correlations of data, in Proc 3rd Int. Conf. on Permafrost, Vol. 1, Nat. Res. Council of Canada, 40-46.

Morrissey, L A (1986). Mapping permafrost in the boreal forest with Thematic Mapper satellite data. Photo. Eng. Rem. Sens. (52),9,1513-1520.

Nelson, F E (1986). Permafrost distribution in central Canada: application of a climate-based predictive model. Ann. Ass. Amer. Geog. (76), 4,550-569.

Ng, E and Miller, P C (1977). Validation of a model of the effect of tundra vegetation on soil temperatures. Arc. Alp. Res. (9),2,89-104.

Viereck, L A, Dyrness, C T, Van Cleve, K, and Foote, M J (1983). Vegetation, soils, and forest productivity in selected forest types in interior Alaska. Can. Jour. For. Res. (13),5, 703-702.

Viereck, L A and Lev, D J (1983). Long-term use of frost tubes to monitor the annual freeze-thaw cycle in the active layer, in Proc. 4th Int. Conf. on Permafrost, Fairbanks, Alaska.