# PERMAFROST DEGRADATION AND ECOLOGICAL CHANGES ASSOCIATED WITH A WARMING CLIMATE IN CENTRAL ALASKA

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**Abstract.** Studies from 1994–1998 on the Tanana Flats in central Alaska reveal that permafrost degradation is widespread and rapid, causing large shifts in ecosystems from birch forests to fens and bogs. Fine-grained soils under the birch forest are ice-rich and thaw settlement typically is 1–2.5 m after the permafrost thaws. The collapsed areas are rapidly colonized by aquatic herbaceous plants, leading to the development of a thick, floating organic mat. Based on field sampling of soils, permafrost and vegetation, and the construction of a GIS database, we estimate that 17% of the study area (263,964 ha) is unfrozen with no previous permafrost, 48% has stable permafrost, 31% is partially degraded, and 4% has totally degraded. For that portion that currently has, or recently had, permafrost (83% of area), ~42% has been affected by thermokarst development. Based on airphoto analysis, birch forests have decreased 35% and fens have increased 29% from 1949 to 1995. Overall, the area with totally degraded permafrost (collapse-scar fens and bogs) has increased from 39 to 47% in 46 y. Based on rates of change from airphoto analysis and radiocarbon dating, we estimate 83% of the degradation occurred before 1949. Evidence indicates this permafrost degradation began in the mid-1700s and is associated with periods of relatively warm climate during the mid-late 1700s and 1900s. If current conditions persist, the remaining lowland birch forests will be eliminated by the end of the next century.

## 1. Introduction

Predicted global warming (Houghton et al., 1996) has focused concerns over the effects of increased air temperatures on the distribution and degradation of permafrost worldwide (Osterkamp, 1983; Smith, 1983; Anisimov, 1989; Zoltai and Vitt, 1990; Anisimov and Nelson, 1996; Nelson et al., 1993). In the northern hemisphere, permafrost occurs on 25.5 million ha (including glaciers) or about 23% of the land area and 17% of the permafrost area has discontinuous (50–90% of area frozen) permafrost (Brown et al., 1997; Brown and Haggerty, 1998). Permafrost and associated ecosystems in the southern boreal forest region, where permafrost

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is relatively ‘warm’ (mean annual temperature 0 to –3 °C), thin, and discontinuous (Vitt et al., 1994; Anisimov and Nelson, 1996), are particularly sensitive to the effects of climate change.

The degradation of permafrost can lead to large changes in ecosystems, land use and infrastructure that rely on permafrost for a foundation (Osterkamp, 1983; Osterkamp et al., 1998). In addition to physically supporting ecosystems, permafrost controls soil temperature and moisture, subsurface hydrology, rooting zones and micro topography (Woo, 1992). For forests on ice-rich permafrost, thawing of permafrost can lead to the wholesale conversion of ecosystems from terrestrial to aquatic or wetland systems (Drury, 1956; Woo, 1992; Vitt et al., 1994; Osterkamp et al., 2000) and also can severely impact upland sites (Osterkamp et al., 1998). Climatic change can alter permafrost directly through changes in air temperatures and soil heat conduction, or indirectly through changes in wildfire frequencies leading to changes in the soil thermal regime (Van Cleve and Viereck, 1983; Swanson, 1996; Burn, 1998; Osterkamp et al., 2000). Prediction of permafrost distribution and its response to climate change, however, is complicated by the effects of local variation in vegetation, soil moisture and thermal properties, and snow cover (Smith, 1975; Smith and Riseborough, 1996).

Thermokarst features and permafrost degradation are widespread in Canada (Thie, 1974; Senyk and Oswald, 1983; Zoltai and Vitt, 1990; Zoltai, 1993; Kwong and Gan, 1994; Vitt et al., 1994; Halsey et al., 1995; Laberge and Payette, 1995; Camill and Clark, 1998), Russia (Shur, 1977; Anisimov, 1989; Kondratjev et al., 1993; Pavlov, 1994), Mongolia (Sharkuu, 1998), China (Cheng, 1983; Ding, 1998) and Alaska (Osterkamp et al., 2000). In Canada, Thie (1974) estimated that 75% of the permafrost at the southern limit of discontinuous permafrost (estimated to originally cover 60% of the area) in Manitoba had degraded by 1967 and that extensive thawing began 100–200 y ago. Vitt et al. (1994) interpreted the differences in landforms related to permafrost aggradation and degradation to indicate that permafrost was more extensive in the past and has retreated northward during the last 100–150 y. In China, where permafrost underlies ∼20% of the land area, Ding (1998) estimates that the southern limits of permafrost are moving northward at ∼1.5–3 km per year. In the Selenge River Basin in Mongolia, where continuous and discontinuous permafrost occupy 30% of the area, Sharkuu (1998) estimated that ∼75% of the permafrost is degrading and that within 50 years the area underlain by permafrost will decrease by 25–35%. In Alaska, where 85% of Alaska is within permafrost zones, numerous studies (Wallace, 1948; Drury, 1956; Ferrians et al., 1969; Osterkamp, 1983; Jorgenson and Kreig, 1988; Osterkamp et al., 1998; Osterkamp et al., in press) have described or modeled permafrost degradation in the discontinuous permafrost zone. There does not appear to be any information, however, quantifying the extent or rates of degradation over a large area in Alaska.

We have recently identified a 2000 km$^2$ area of permafrost degradation in interior Alaska in flat lowlands south of the Tanana River. Previous studies have described the general condition of the permafrost (Walters et al., 1998) and the development of vegetation in thermokarst depressions (Racine et al., 1998) in the area and we rely on those studies for more complete characterization of permafrost characteristics and vegetative composition. The present study attempts to understand the extent, history and rates of permafrost degradation over this large area, and some of the ecological changes that result from this degradation. The objectives of this study were to: (1) determine the relationships between permafrost and vegetation types, (2) map the distribution of permafrost conditions based on ecological relationships over the entire area, and (3) evaluate the pathways and rates of recent change of a portion of the area using airphoto analysis and radiocarbon dating.

## 2. Study Area

The study focused on a portion (263,964 ha) of the Tanana Flats within the Tanana River valley lowlands. This area, which is part of Fort Wainwright, is bordered on the north by the Tanana River and on the south by the foothills of the Alaska Range (Figure 1). The continental climate of central Alaska (Fairbanks) has an average annual temperature of –3.3 °C, with absolute extremes ranging from –51 to 38 °C. The average annual precipitation is 28 cm, of which 37% falls as snow from mid-October through April. Maximum annual snow depths, achieved by February or March, average 75 cm. The area is situated on the toe slope of a large alluvial fan complex built from Holocene sediments derived from the Alaska Range (Péwé, 1966). Permafrost thickness was 47 m in one borehole in the area (Chacho et al., 1995). Both surface and subsurface waters move across the flats from southeast to northwest and the groundwater discharges in numerous springs in the central to northern portion (Racine and Walters, 1994). Vegetation patterns on the flats are highly patchy and diverse due to the interrelation among geomorphology, slope, aspect, hydrology, permafrost, and fire (Jorgenson et al., 1999; Racine et al., 1998).

## 3. Methods

### 3.1. FIELD SURVEYS

Most of the fieldwork was undertaken as part of an ecological land classification project for the U.S. Army at Fort Wainwright, Alaska (Jorgenson et al., 1999). Between 1994 and 1998, eight ∼1-km-long transects (labeled with their field ID’s) were located on the Tanana Flats (Figure 1) in areas that maximized the range of possible permafrost and vegetation conditions. Relative elevations of the ground surface were measured along each transect with an auto-level and rod. Then at selected sampling points representing the different ecosystem types along these transects, measurements were made of permafrost occurrence, soil-stratigraphy using standard methods (SSDS, 1993), vegetation composition (visual estimates

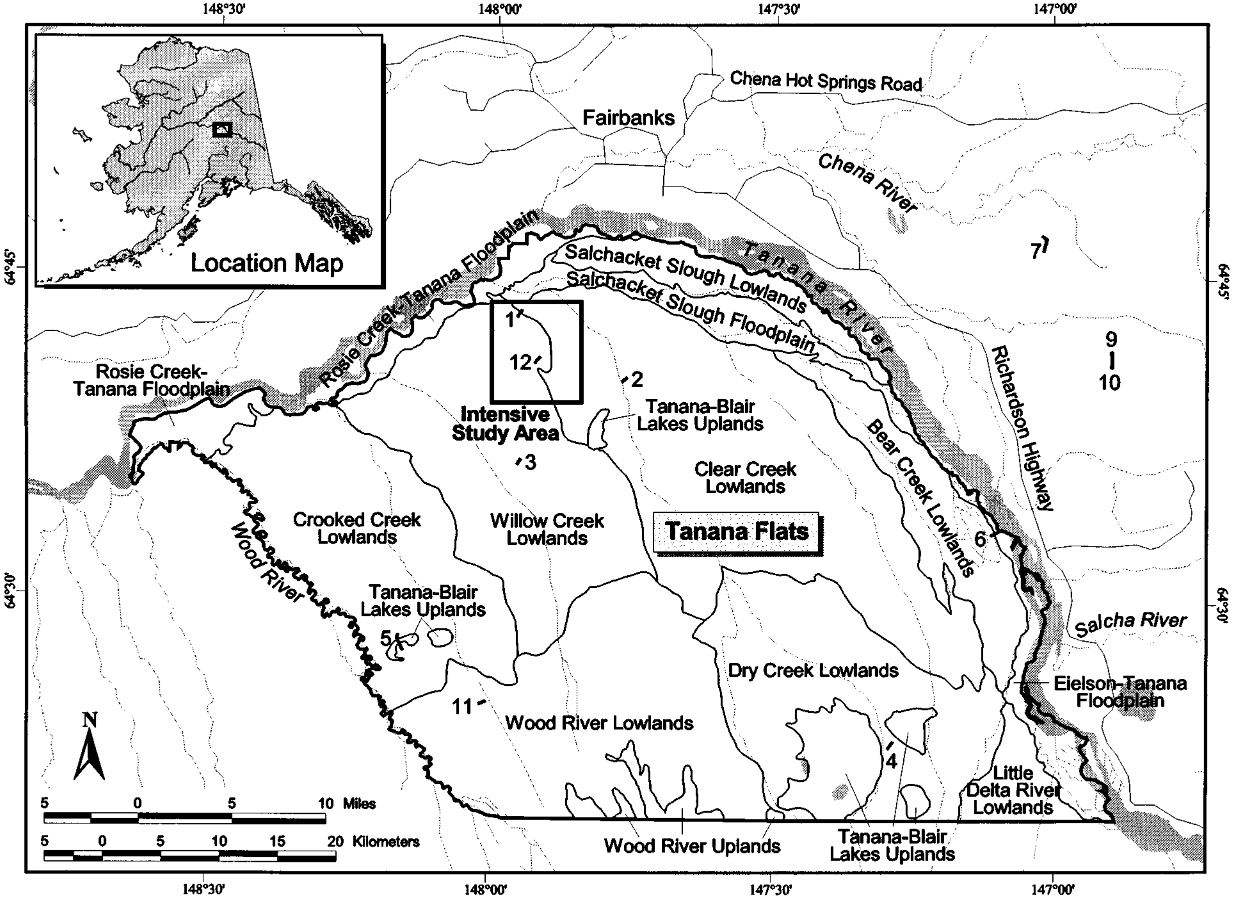

*Figure 1.* Map of the Tanana Flats in central Alaska showing the limits of the overall study area and the intensive study area. Subdivisions within the Tanana Flats indicate ecosubdistricts with repeating associations of geomorphology and vegetation. Numbers indicate intensive sampling transects.

of % cover by species) and structure, and water quality for surface or subsurface water. Permafrost occurrence was evaluated with soil pits and steel probes. At some locations along transects 1 and 12, 7.5 cm diameter cores of the permafrost were obtained with a SIPRE core to evaluate ground-ice structures (Shur and Jorgenson, 1998). Visual estimates were made of the percent volume of excess ice for each core segment with uniform structure, and total percentage of visible excess ice for each core was calculated based on the mean of the segment values. Methods are described in more detail in Jorgenson et al. (1999).

Soil temperatures were collected at single locations along transect 1 within 5 ecosystem types using Campbell Scientific, Inc., CR10 dataloggers. Thermistors typically were installed at 1.5 m above the ground and at 5, 50, 100, 200, and 300 cm below the ground surface. Temperatures were measured hourly. Mean annual ground temperatures (MAGT) were calculated for periods with complete data, between 1995 and 1999.

### 3.2. CLASSIFICATION AND MAPPING

We used an integrated terrain unit approach for ecosystem classification and mapping that included separate classifications for geomorphology and vegetation. Geomorphic units were classified according to a system based on landform-soil characteristics originally developed by Kreig and Reger (1982) and modified to include organic units described in wetland classification for Canada (National Wetlands Working Group, 1988). We also relied on the geologic map of the Fairbanks Quadrangle (Péwé et al., 1966). Vegetation was classified to Level IV of the Alaska Vegetation Classification (Viereck et al., 1992).

An integrated terrain unit map was developed using linework obtained from the vegetation map produced by the Soil Conservation Service (SCS/ADNR, 1990). SCS polygons were transferred to acetate and overlain on 1995 1:24,000 true-color aerial photographs. Polygons were recoded with an integrated-terrain-unit system that included both a geomorphology and vegetation code, and boundaries redrawn where necessary. For areas lacking SCS mapping, polygon boundaries were delineated using 1995 aerial photography. The boundaries were digitized and geo-rectified using control points obtained from USGS topographic maps.

A map of permafrost classes was generated using the GIS database. Six classes were differentiated: continuous (>90% frozen), discontinuous (50–90% frozen with no obvious collapse scar features, discontinuous-degrading (initial stage of degradation, abundant collapse-scar features), sporadic-degrading (10–50% frozen, advanced stage of degradation), unfrozen-recently degraded (<10% frozen, large collapse-scar feature), and unfrozen (no collapse-scar features evident, primarily south-facing slopes and young alluvium). Each of the 276 integrated terrain units was assigned a permafrost class based on observed (using frequency of occurrence) and inferred (when ground data was missing) relationships between permafrost, vegetation and geomorphology.

### 3.3. CHANGE DETECTION

Analysis of the extent and rate of change associated with permafrost degradation was performed by interpretation of aerial photographs (1949, 1978, and 1998), radiocarbon dating of the organic material from the base of the fen peat, and tree coring. To facilitate comparisons on the aerial photographs, the photographs were scanned, georeferenced to each other using ER Mapper software with an RMS accuracy of 4 m, and printed in a universal tranverse mercator (UTM grid) projection with 250 m graticules. First, changes in the areal extent of ecosystems were determined by classifying ecosystem types at 300 points systematically distributed at 250 m intervals across the intensive study area for each year of coverage. Secondly, the lateral rates of movement of the forest-fen margin were determined at 25 locations widely distributed across the intensive study area (Figure 1) by measuring distances relative to the UTM grid. At 10 locations that occurred adjacent to large fens, the distance to the middle of the fen also was measured.

Radiocarbon dating was done by Beta Analytic, Inc. on 23 wood and peat samples obtained from the thermokarst features. Dates are reported as $^{14}$C years before 1950 and calibrated calendar year range (95% probability) following the methods of Stuiver and Reimer (1993). Multiple intercepts were noted, however, for those that were $>$1900 and were excluded because we know from the airphoto analyses that the samples could not have originated from that period. For analysis, the calibrated intercept ages were used; in cases when there were multiple intercepts, the average of the intercepts was used for each of those samples. For samples that were calibrated to be ‘modern’, an age of 1850 was assigned.

Historical data for mean annual air temperature and winter accumulative total snowfall were obtained from the summaries developed by Susan Bowling (ACRC, 1999). Paleoclimatic data for summer temperatures developed from tree-rings (D’Arrigo and Jacoby, 1993) and multiple proxy indicators Overpeck et al. (1997) were obtained from the National Geophysical Data Center (www.ngdc.noaa.gov/paleo/paleo.html). Linear regression analysis was used to calculate climatic trends over the period of instrumental records.

## 4. Results

### 4.1. RELATIONSHIP OF PERMAFROST TO ECOSYSTEM CHARACTERISTICS

There were large differences in soil, vegetation, and permafrost characteristics among ecosystem types, even though parent material was similar. Soil stratigraphy along Transect 1 revealed that geomorphic processes can be divided into 4 depositional and erosional regimes (Figure 2). First, the area was underlain by gravel associated with glaciofluvial outwash during glacial retreat during the early Holocene. Second, the gravel was overlain by thick (2–4 m) silty, abandoned-floodplain

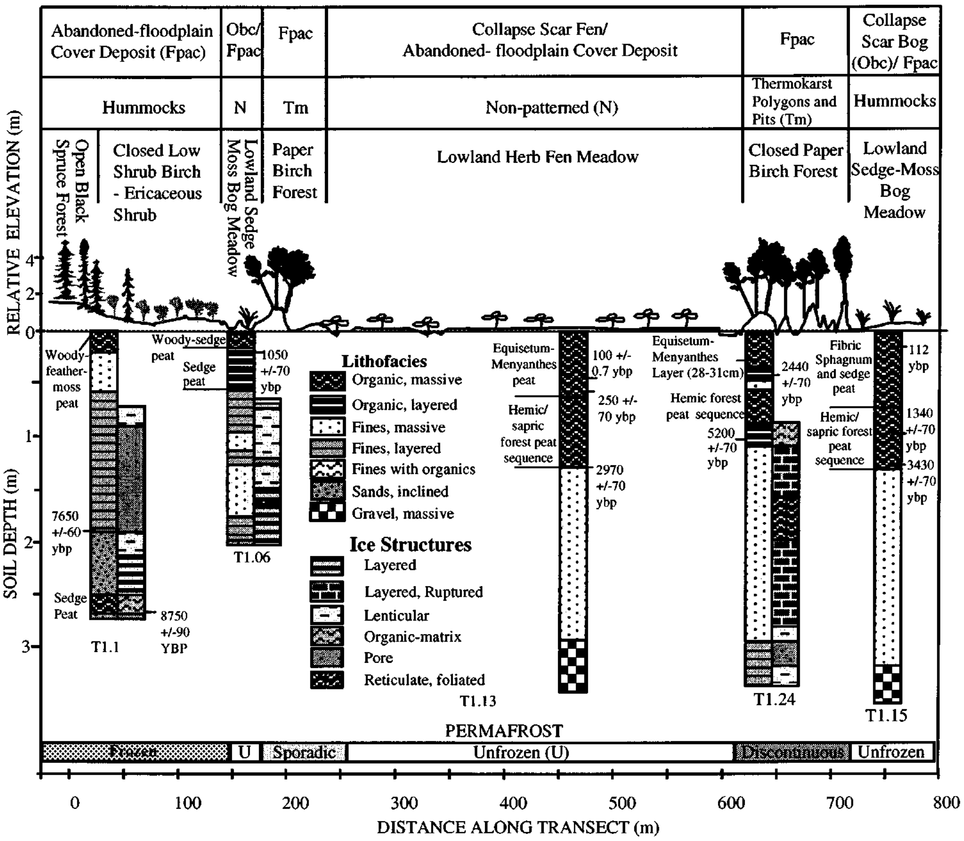

*Figure 2.* Toposequence at Transect 1 illustrating the relationships among topography, geomorphology, surface form, vegetation, soil stratigraphy, and permafrost. For each core, lithofacies are portrayed in left column and ice structure in right column when present.

cover deposits created by a combination of fluvial and eolian processes. Third, fine-grained cover deposits were capped by a moderately thick layer of peat derived mostly from woody forest peat that has accumulated under stable geomorphic conditions lacking in fluvial or eolian deposition. Fourth, collapse-scar bogs and fens have resulted from permafrost degradation, thaw settlement, and paludification. Rapid accumulation of *Sphagnum* peat in the bogs and herbaceous peat in the fens has resulted in thick organic deposits. Bogs form under an ombrotrophic precipitation regime, whereas, collapse-scar fens form where groundwater movement contributes to a higher nutrient regime. Linear-shaped fens were differentiated from circular bogs by their surface pattern (Figure 3), higher electrical conductivity and pH values of the soil-water, and herbaceous peat. Ecosystem characteristics, and their permafrost regimes, are described in more detail below.

Lowland black spruce forests had thin, surface organic horizons composed of fibric to hemic woody and feathermoss material, and a somewhat less thick active

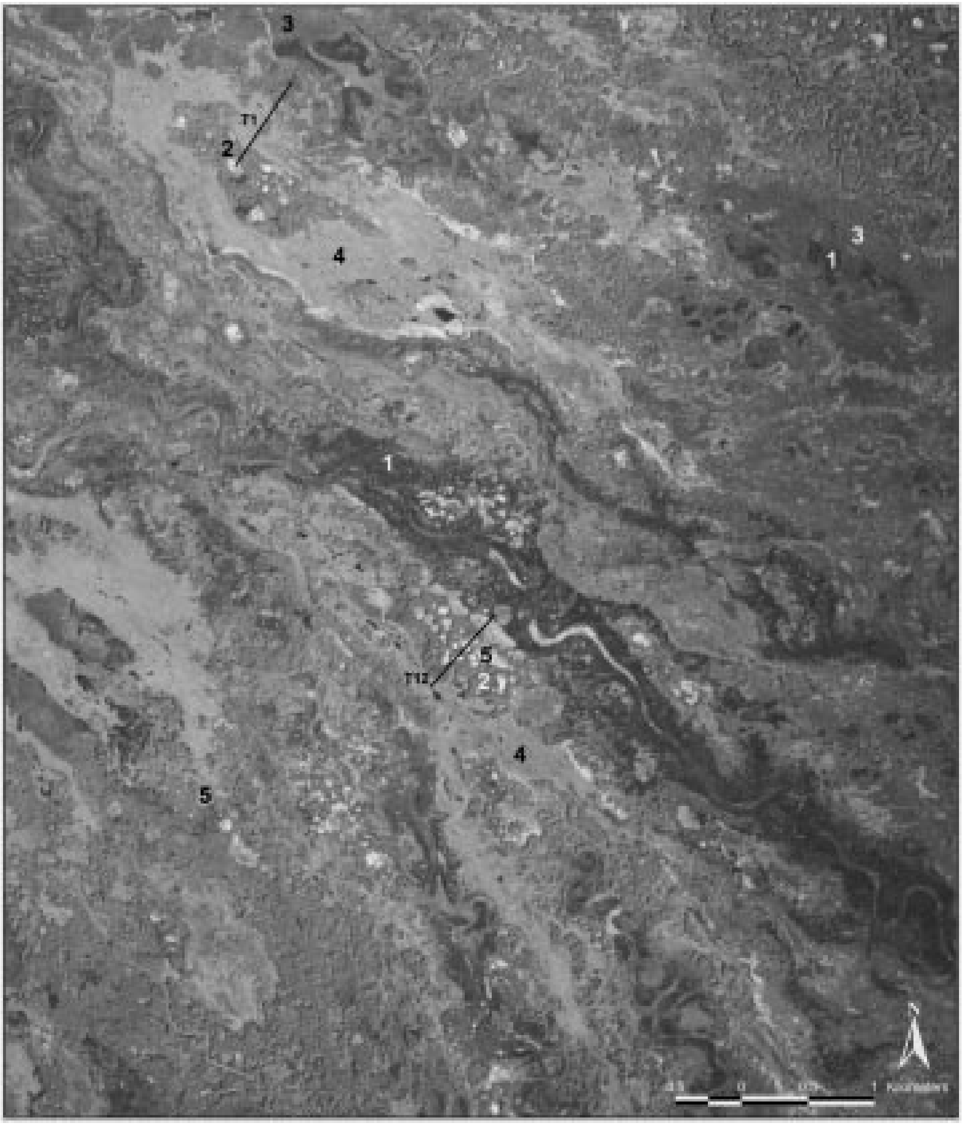

*Figure 3.* Aerial photograph (1978, color-infrared) of the intensive study area within the Willow Creek lowlands portion of the Tanana Flats, central Alaska. Numbers indicate dominant ecosystem type: (1) black spruce forest, (2) birch forest, (3) low scrub, (4) fen meadow, and (5) bog meadow. Sampling transects T1 and T12 also are shown.

layer (Table I). The underlying permafrost had low to intermediate ice contents, ice structures dominated by lenticular and pore ice, and a MAGT of –0.6 °C at a depth of 3 m (Walters et al., 1998). The vegetation had an open to closed canopy dominated by black spruce (*Picea mariana*), although white spruce (*P. glauca*) and tamarack (*Larix laricina*) occasionally occurred. The understory included Labrador

TABLE I

Soil properties of the dominant ecosystems occurring on the Tanana Flats, central Alaska

| | Lowland black spruce for. | Lowland mixed forest | Lowland birch forest | Lowland low scrub | Lowland tussock bog | Lowland bog meadow | Lowland fen meadow |
|---|---|---|---|---|---|---|---|
| Water depth (cm)[a] | | | | | | | |
| Mean | –50 | –65 | –42 | –30 | –16 | –6 | 18 |
| SD | 30 | 25 | 23 | 24 | 36 | 4 | 29 |
| *n* | 28 | 7 | 5 | 10 | 2 | 7 | 8 |
| Surface organic depth (cm)[b] | | | | | | | |
| Mean | 15 | 22 | 46 | 45 | 35 | 100 | 94 |
| SD | 8 | 17 | 35 | 28 | 49 | 28 | 97 |
| *n* | 31 | 7 | 6 | 11 | 2 | 8 | 7 |
| Thaw depth (cm)[c] | | | | | | | |
| Mean | 53 | 70 | 77 | 58 | 56 | Unfrozen | Unfrozen |
| SD | 23 | 18 | 31 | 16 | 21 | | |
| *n* | 18 | 4 | 5 | 7 | 2 | | |
| Permafrost occurrence | | | | | | | |
| % | 82 | 83 | 100 | 78 | 100 | 0 | 0 |
| *n* | 22 | 6 | 6 | 9 | 2 | 7 | 6 |
| Annual ground temperature at 3 m (°C)[d] | | | | | | | |
| Mean | –0.6 | ND | –0.2 | –0.4 | ND | 1.4 | 2.6 |
| Range | –0.3 to -0.9 | ND | –0.2 | –0.2 to –0.6 | ND | 0.9 to 1.8 | 2.4 to 2.8 |
| Microtopography | Hummocky | Pits and mounds | Pits and mounds | Hummocky | Hum-mocky | Flat | Flat |
| Visible excess ice (% vol.) | | | | | | | |
| Mean[e] | 18 | 12 | 43 | 10 | 8 | Absent | Absent |
| Range | 9–33 | 8–15 | 26–57 | 1–26 | 8 | | |
| *n* | 3 | 2 | 7 | 2 | 1 | | |
| Ice structure[f] | Lenticular, pore ice | ND | Layered, ruptic layered | Lenticular, layered | ND | Absent | Absent |
| Permafrost regime | Stable | Degrading | Degrading | Stable | Stable | Degraded | Degraded |

[a] Depth to water table negative when below the ground surface.

[b] Organic depth is for continuous surface organic horizons and do not include buried horizons.

[c] Thaw depths are from sites with permafrost and do not include depths from sites where permafrost was not encountered.

[d] Soil temperatures are from single locations along Transect 1, period of record variable between 1995 and 1998.

[e] Mean volume of excess ice obtained by averaging visual estimates for all segments from top 2 m of each frozen core.

[f] Ice structures from Shur and Jorgenson (1998), except ruptic layered which has small silt lenses suspended in ice probably formed from heaving and breaking of layered ice.

tea (*Ledum groenlandicum*), bog blueberry (*Vaccinium uliginosum*), lingonberry (*V. vitis-idaea*), feathermoss (*Hylocomium splendens*), and often *Sphagnum* spp. Lowland low scrub had similar soil properties, but the vegetation had an open to closed canopy of low shrubs dominated by dwarf birch (*Betula nana*) and ericaceous shrubs (*L. groenlandicum*, *V. uliginosum*, *V. vitis-idaea*). Scattered trees (*P. mariana*, *L. laricina*) were common and other plants included bluejoint (*Calamagrostis canadensis*), leatherleaf (*Chamaedaphne calyculata*), and *Sphagnum* mosses. We regard the permafrost of these ecosystems to be relatively stable because of the slightly colder soil temperatures and lack of thermokarst features. While lower ground ice contents in this ecosystem can contribute to less prominent thermokarst features, where thermokarst has occurred the depressions are readily apparent on the ground and on aerial photography.

Lowland birch forests are common on the slightly elevated (1–2 m) permafrost plateaus adjacent to the fens, presumably as a result of lowering of the water table, aeration of soils, and lack of spruce regeneration in the thick organic soils. Organic material was dominated by fibric to hemic woody forest peat, but included layers of herbaceous fen peat indicating that the forests had developed on permafrost that had aggraded under previous fen conditions. The underlying permafrost had high ice content, ice structures dominated by layered, ruptured layered (presumably cracked and displaced by heaving forces), and foliated reticulate ice, and a constant temperature of –0.2 °C throughout the year at the 3-m depth (Table I). Unfrozen water content must be substantial because of the warm temperature and because the temperature did not deviate from the melting/freezing point, indicating temperatures were constrained by the latent heat of fusion associated with unfrozen and frozen water. The vegetation had a closed overstory dominated by paper birch (*Betula papyrifera*), although white and black spruce are often present in the understory. Other plants included prickly rose (*Rosa acicularis*), bluejoint, and common horsetail (*Equisetum arvense*). Dead trees were prevalent along the rapidly collapsing margins and thaw pits were abundant in the interior of the forests (Figures 4 and 5). The pits supported numerous aquatic species including duckweed (*Lemna minor*), bur marigold (*Bidens cernua*), wild calla (*Calla palustris*), marsh five fingers (*Potentilla palustris*), and *Sphagnum* mosses (Racine et al., 1998). Lowland mixed forests were similar, but the overstory included white and black spruce. We regard permafrost in these ecosystems to be degrading because of the relatively warm temperatures and the prevalence of thaw pits.

The lowland fen meadows, which have formed in degraded collapse scars, lacked permafrost, at least to the 4-m depth. Lowland fen meadows had thick organic accumulations at the surface comprised of herbaceous aquatic species, mostly buckbean (*Menyanthes trifoliata*) and swamp horsetail (*Equisetum fluviatale*) and had water at or above the surface. Paper birch stems frequently were detected at the base of the fen peat, and below the fen peat there was a thick layer of sapric peat that was derived from the forest peat formed in the birch forests. The MAGT at the 3 m depth was relatively high (2.6 °C) during the year, possibly due to the influence of groundwater. Following collapse of the forest, the fen meadow develops through several stages of paludification that (1) is initiated with the ‘moat’ that forms immediately adjacent to the collapsing banks and is colonized by minerotrophic species (mostly *Calla palustris* and *Carex rostrata*), (2) develops into large expanses of buckbean and swamp horsetail and other herbaceous plants (*C. utriculata*, *C. aquatilis*, *Potentilla palustris*, *Typha latifolia*, *Cicuta mackenzieana*, and *Galium trifidum*) and (3) in later stages includes small, round, slightly

*Figure 4.* Aerial view of dying trees along the margin of lowland birch forests resulting from rapid permafrost degradation on the Tanana Flats, central Alaska.

*Figure 5.* View of thermokarst pit with dead birch trees and aquatic vegetation in the water-filled center. Live trees on the margins were ∼50–65 years old, while dead trees in the center were ∼30–40 years old.

raised areas with willows (*Salix candida*) and sweet gale (*Myrica gale*) presumably associated with uplifting from accumulating peat (Racine et al., 1998).

The lowland bog meadows also occurred in old collapse scars without permafrost, but had thick peat accumulations of *Sphagnum* and sedge peat near the surface and sapric forest peat near the base. The MAGT (1.4 °C) at a depth of 3 m was relatively warm. Vegetation was dominated by sedges (*Carex aquatilis*, *Eriophorum russeolum*, *E. angustifolium*) and *Sphagnum* spp., while bluejoint and small bog cranberry (*Oxycoccus microcarpus*) were common. As the thawing front moves into the birch forest from the fen, these bogs become incorporated into the fen and can be recognized from the air as circular patches.

### 4.2. PERMAFROST DISTRIBUTION AND STATUS

A map of permafrost regimes was developed based on associations of permafrost characteristics with other ecosystem properties and the subsequent recoding of the integrated terrain units (geomorphology/vegetation combinations) in the GIS database. The permafrost map (Figure 6) reveals that 17% of the area was unfrozen and was associated with active and inactive floodplains with various vegetation types, south-facing upland loess and residual soils with various vegetation types, lacustrine deposits, and gravelly abandoned floodplains except those with low scrub vegetation. In contrast, 44% of the area had stable, continuous permafrost and was associated with abandoned floodplain cover deposits with black spruce forest, low scrub, and tussock bog. Stable, discontinuous permafrost covered 4% of the area and was associated with gravelly lowland abandoned channel complexes, lowland slope drainage complexes, and gravelly abandoned floodplains with low scrub.

The three classes of degrading permafrost comprised 35% of the area: The unfrozen, recently degraded class covered 4% of the Tanana Flats and was associated with thermokarst ponds, abandoned floodplain cover deposits with bog and fen meadows, and a portion of the human-disturbed class. The sporadic degrading class covered 15% of the area and was associated with abandoned floodplain cover deposits with scrub fen and lowland scrub-thermokarst complex. The discontinuous degrading class covered 16% of the area and was associated with abandoned floodplains cover deposits with mixed forest, birch forest, and tall scrub and lowland forest thermokarst complex. After subtracting the unfrozen areas associated with floodplains and south-facing slopes (17% of area) that were not the result of recent degradation, we estimate that 42% of the permafrost has undergone some degree of degradation, as indicated by partial (thermokarst complexes) to total collapse of the surface.

Because these estimates were based on relationships of permafrost conditions to ecosystem properties, there is some uncertainty associated with the estimates. Ecosystem types for which we had few samples, and thus less reliable estimates, include lowland scrub fen, upland moist mixed forest (occurs mostly on north-facing slopes), low and tall scrub on gravelly abandoned floodplains, and lowland

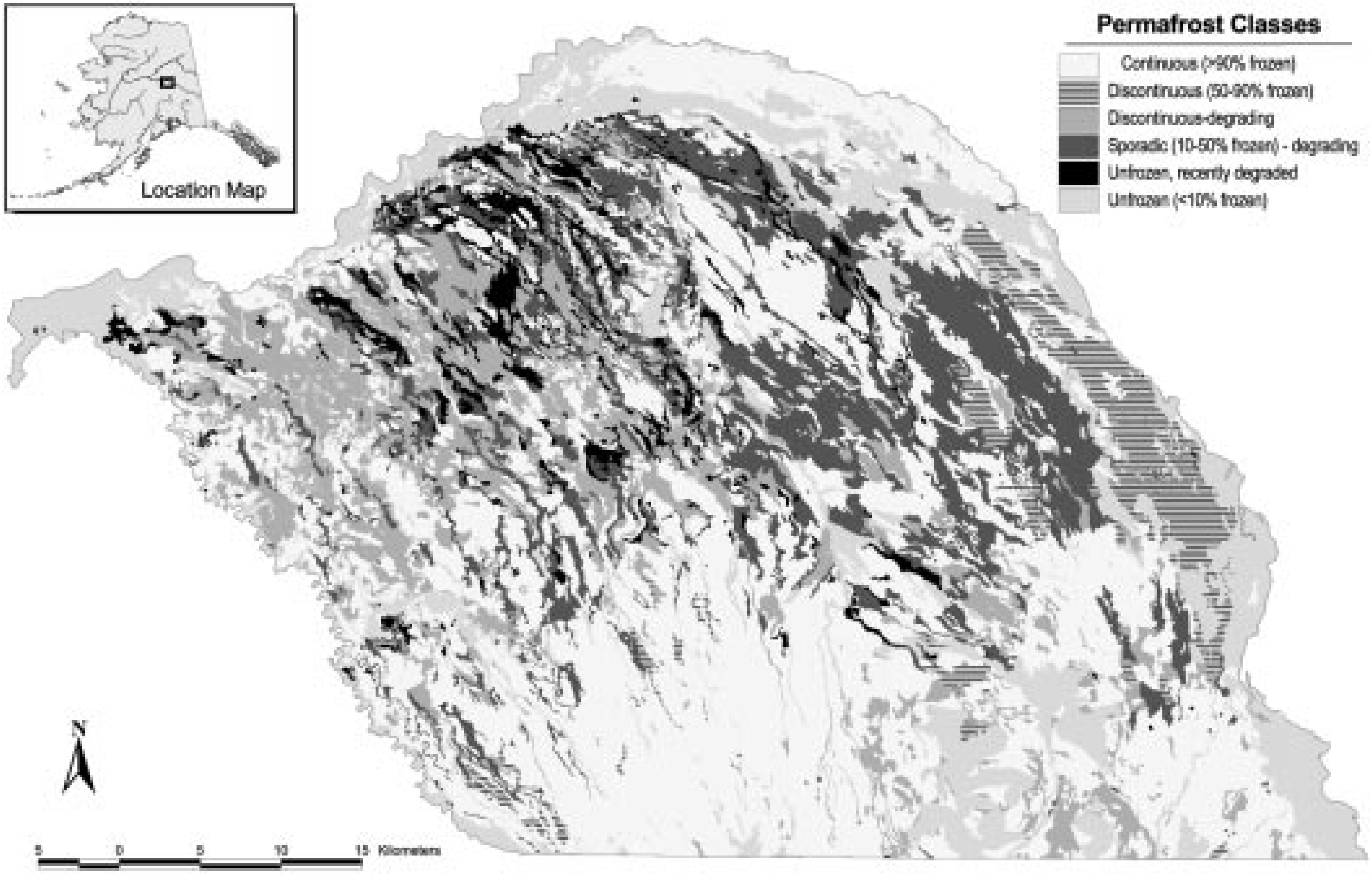

*Figure 6.* Map of permafrost distribution on the Tanana Flats, central Alaska, based on association of permafrost characteristics to other ecosystem properties.

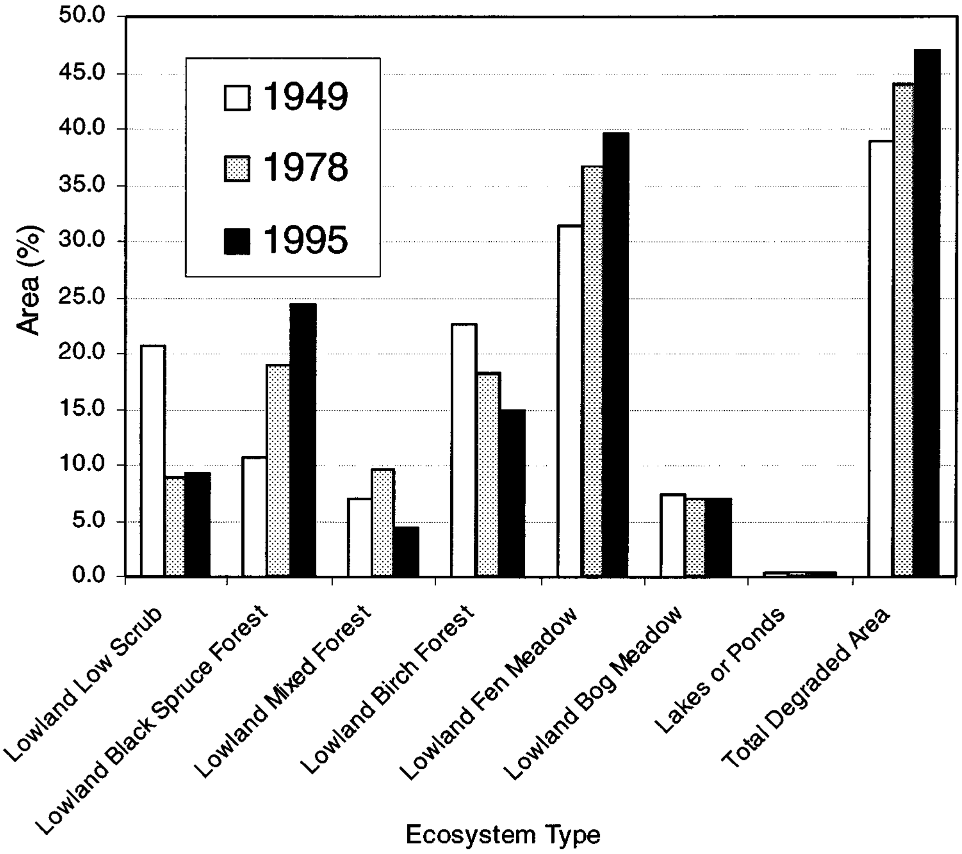

*Figure 7.* Changes in areal extent of ecosystems on the Tanana Flats based on interpretation of aerial photography taken in 1949, 1978, and 1995.

abandoned channel complex. The permafrost status of gravelly abandoned floodplains is particularly problematic because the soils were difficult to sample at depth and they are relatively thaw-stable so thermokarst features are lacking. These ecosystem types, for which permafrost status is uncertain, covered 10% of the area.

## 4.3. PATTERNS AND RATES OF DEGRADATION

We examined permafrost degradation at three spatial scales that included a macrosite (1:15,000) analysis of a small area (3.5 by 5.5 km) in the Willow Creek lowlands where degradation was most evident, mesosite (1:5,000) mapping of boundary changes of two rapidly degrading ‘birch islands’ surrounded by fens, and microsite (1:100) sampling of tree ages in small thaw pits within the birch forests. At the macrosite scale, analysis of changes evident on aerial photography from 1949, 1978, and 1995 revealed rapid changes in the areal extent of ecosystems (Figure 7). Ecosystems that increased in area included lowland fen meadows (from

31% to 40%) and lowland black spruce forests (from 11% to 24%). In contrast, decreases were evident for lowland birch forests (from 23% to 15%, a proportional decrease of 35%) and lowland low scrub (from 21% to 9%). Little change was evident for lowland bog meadows and ponds, and lowland mixed forests increased at first and then decreased. Overall, the extent of totally degraded permafrost (fen, bogs, and ponds) increased from 39% to 47% (a proportional increase of 21%). When lowland birch forests were included as an ecosystem undergoing partial degradation, 62% of the area had undergone partial or total degradation. This is considerably higher than the estimate (42%) for degrading permafrost areas on the larger Tanana Flats. Given that totally degraded areas already covered 39% of the area in 1949, results indicate that 83% (39/47) of the degradation observed by 1995 occurred before 1949. This estimate is based on the assumption that the area was originally continuously frozen. We believe this assumption is valid because buried forest soils and tree stems, which are associated with permafrost conditions in this area, were present in all fens and bogs that we examined.

The photographic analysis also revealed the pathways along which ecosystems have changed over the 46-y period (Figure 8). We have divided these into two main pathways, successional replacement of dominant species in the canopy after fire, and radical alteration due to permafrost degradation. We attribute changes in lowland low scrub and lowland mixed forest into lowland black spruce forests to successional replacement of the canopy by black spruce. Also, a small amount of lowland birch forests has been replaced by lowland mixed forests. In contrast, we attribute the changes from lowland birch forests to lowland fen and bog meadows to be due to permafrost degradation. A small amount of lowland bog meadows have been replaced by lowland fen meadows as the bogs, which occur as isolated patches within the birch forests, become connected to the fens when the forest collapses.

At the mesosite scale, rapid changes occurred in the areal extent of two ‘birch islands’ of degrading permafrost dominated by lowland birch and black spruce forests between 1949 and 1995 (Figure 9). The island crossed by Transect 1 decreased in area from 77 to 54 ha (30%), while the island crossed by Transect 12 decreased from 56 to 39 ha (30%) over the 46 y period. These rates are in close agreement with the 35% decrease in lowland birch forests across the larger intensive sampling area. At this rate (0.76% of the 1995 area per year), the remaining birch forest will be eliminated in less than a century (2085). The mean lateral rate of thaw or retreat of the forest margins was 0.6 m/y (SD ± 0.4). Higher rates (1.0–1.7 m/y) were measured at 12% of the sites and low rates ($\leq$0.1 m/y) were measured at 8% of the sites, indicating that degradation is consistent throughout the area.

At the microsite scale, thaw ‘pits’ were abundant within the lowland birch forests and were in varying stages of collapse, ranging from slight depressions with intact vegetation to small (10–30 m), circular ponds filled with emergent vegetation (Figure 5). In the early stages of development, the flooded pits contained numerous dead birch trees at the bottom with live trees along the margins leaning in toward

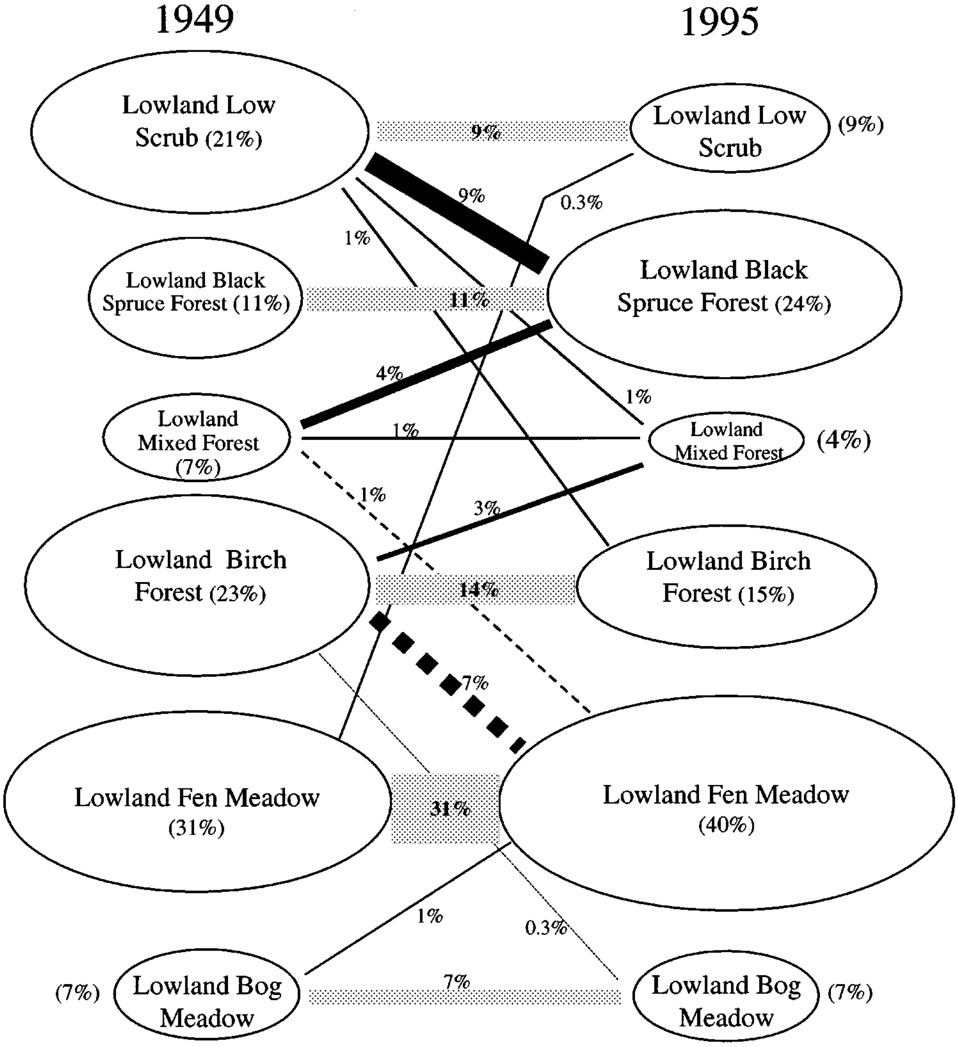

*Figure 8.* Pathways of change in areal extent of ecosystems on the Tanana Flats from 1949 to 1995. Sizes of ellipses and lines are proportional to percent of area and values are for percent area. Gray lines indicate no change, solid black lines indicate succession of canopy species, and dashed lines indicate permafrost degradation.

the center. In the pits where trees were still present, the presence of birch trees helped determine the rate at which the pits were collapsing; the largest live trees were ~50–60 y, indicating the pits did not exist before ~1940. Dead trees in the pits typically were ~30–40 y, indicating that degradation into water-filled pits took ~30–40 y, assuming that birch died soon after collapse and inundation. Many pits do not have dead standing trees in the middle so the age of these is unknown.

*Figure 9.* Changes in boundaries of two permafrost plateaus (‘birch islands’) from 1949 (thick line) to 1995 (thin line) near transects 1 and 12 on the Tanana Flats, central Alaska.

### 4.4. TIMING OF DEGRADATION

We estimate that permafrost degradation on the flats was initiated between 1600 and 1750 AD based on the range of mean values from three methods. Radiocarbon dating of five samples of birch wood and bark buried underneath the fen peat and one of sedge peat in a bog (Table II) indicates that thaw initiated about 1740 AD (SD $=$ 160 y, $n = 6$), although there is uncertainty associated with the dating of modern carbon. Most calibrated ages for intercepts cluster in a period between 1650 and 1850, while the extreme range for all calibrated age ranges was 1410–1890. Linear extrapolation of rates of change in lowland fen meadows obtained from the airphoto analysis indicates that degradation was initiated about 1730 AD. Extrapolating the lateral rates of thaw provided the oldest date of initiation at 1620 AD (SD $=$ 305 y, $n = 11$), but also had the largest uncertainty.

The onset of degradation is unlikely to be a uniform event, however, and it is likely that areas started to degrade at different times. In addition, the degradation rate may not be linear over time if degradation was accelerated with climatic warming. If such is the case, most degradation may have happened in the 50–100 years preceding 1949. Because we were not able to resolve potential differences in degradation rates over time given the low precision of our data, and have no basis for calculating nonlinear rates, we believe the use of constant rates was the most reasonable assumption for estimating onset of degradation. Based on the assumption of constant rates, we calculate that 53% of the permafrost degradation occurred since 1850.

The presence of fen peat (always associated with unfrozen conditions in this area) near the soil surface within the birch forests complicates the analysis of permafrost degradation. $^{14}$C dates of 4 samples of laminar, herbaceous organic material from 20–30 cm below the ground surface, had calibrated ages ranging from 1490 to 1950, while all four samples had a calibrated intercept age between 1650 and 1670 (Table II). This indicates that permafrost aggradation and the change from fens to forests occurred in the late 1600s. This helps further constrain the date for the onset of degradation because the permafrost had to form before the subsequent degradation.

### 4.5. CLIMATIC SUMMARY

Both historical and paleoclimatic proxy records indicate substantial warming during the last 100–150 y (Figure 10). Linear regression analysis of climatic records (1906–1998) for Fairbanks, indicate that mean annual air temperatures have increased at a rate of 1.2 °C per 91 y (ACRC, 1999). The increase mostly has been due to increases in summer temperatures, whereas, the trend in winter temperatures showed little change. Relatively warm annual temperatures (mean annual temperatures $>$–2.5 °C) occurred during 1912–1916, 1920–1929, 1937–1944, 1957–1962, 1967–1970, and 1976–1998. Fairbanks weather records also reveal that snow

## TABLE II

Radiocarbon dates obtained from ecosystems along transects 1 and 2 on the Tanana Flats, central Alaska

| Field ID | Depth (cm) | Ecosystem type | Material | Lab no. | Convention $^{14}$C age[a] | Calibrated age range[b] | Calibrated intercept age |
|---|---|---|---|---|---|---|---|
| T1.1 | 186–189 | Black spruce forest | Wood | B90771 | 7650 +/- 60 BP | BC 6600–6410 | BC 6460 |
| T1.1 | 265–271 | Black spruce forest | Sedge | B90772 | 8750 +/- 90 BP | BC 8205–7585 | BC 7770 |
| T1.06 #3 | 10–37 | Shrub bog | Peat | B79630 | 1050 +/- 70 BP | AD 870–1155 | AD 1000 |
| T1.13 #1 | 125–130 | Fen meadow | Basal peat | B79632 | 2970 +/- BP | BC 1400–985 | BC 1205 |
| T1.13 | 40–55 | Fen meadow | Birch bark | B97559 | 100.3 +/- 0.7% | Modern | |
| T1.13 | ∼70 | Fen meadow | Birch wood | B97560 | 250 +/- 70 BP | AD 1470–1880 | AD 1650 |
| T1N-189 | 0 | Fen meadow | Birch stump | B116439 | 100.7 modern | Modern | |
| T1N-200 | 56 | Fen meadow | Birch bark | B116441 | 440 +/- 60 | AD 1410–1635 | AD 1450 |
| T1N-50 m | 50 | Fen meadow | Birch wood | B116442 | 160 +/- 60 BP | AD 1650–1950 | AD 1680, 1745, 1805 |
| T1.15 #4 | 10–20 | Bog meadow | Sphagnum | B79635 | 112.4 +/- 0.7% | Modern | |
| T1.15 #2 | 90–100 | Bog meadow | Peat | B79634 | 1340 +/- BP | AD 615–785 | AD 670 |
| T1.15 #1 | 120–130 | Bog meadow | Basal peat | B79633 | 3430 +/- 70 BP | BC 1910–1535 | BC 1735 |
| T1.24 #1 | 27–34 | Birch forest | Peat | B79636 | 1640 +/- 70 BP | AD 245–570 | AD 415 |
| T1.24a | 41–45 | Birch forest | Peat | B90777 | 2440 +/- 70 BP | BC 200–AD 95 | BC 45 |
| T1.24b | 80–83 | Birch forest | Peat | B90778 | 5330 +/- 70 BP | BC 4335–3980 | BC 4220 |
| T1.24z | 90–110 | Birch forest | Peat | B90779 | 5200 +/- 70 BP | BC 4225–3925 | BC 3985 |
| T1.Deg | 20–30 | Birch forest | Platy layer | B099915 | 220 +/-70 BP | AD 1500–1950 | AD 1660 |
| T12.06 | 28–31 | Birch forest | Platy layer | B97561 | 210 +/-60 BP | AD 1520–1890 | AD 1665 |
| T12.06 | 49–57 | Birch forest | Basal peat | B97564 | 1980 +/- 60 BP | BC 115–AD 135 | AD 30 |
| T12.08 | 45 | Bog meadow | Sedge | B97562 | 110 +/- 0.9% | Modern | |
| T12.08 | 115 | Bog meadow | Peat | B97563 | 490 +/- 70 BP | AD 1310–1365 | AD 1425 |
| T12.11 | 25–30 | Birch forest | Platy layer | B97566 | 190 +/- 50 BP | AD 1640–1890 | AD 1670, 1780, 1795 |
| T12.15 | 30–31 | Birch forest | Platy layer | B97568 | 250 +/- 60 BP | AD 1490–1810 | AD 1650 |

[a] Conventional $^{14}$C years before 1950.

[b] Calibrated age (2 sigma, 95% probability) to calendar year based on INT93CAL curve.

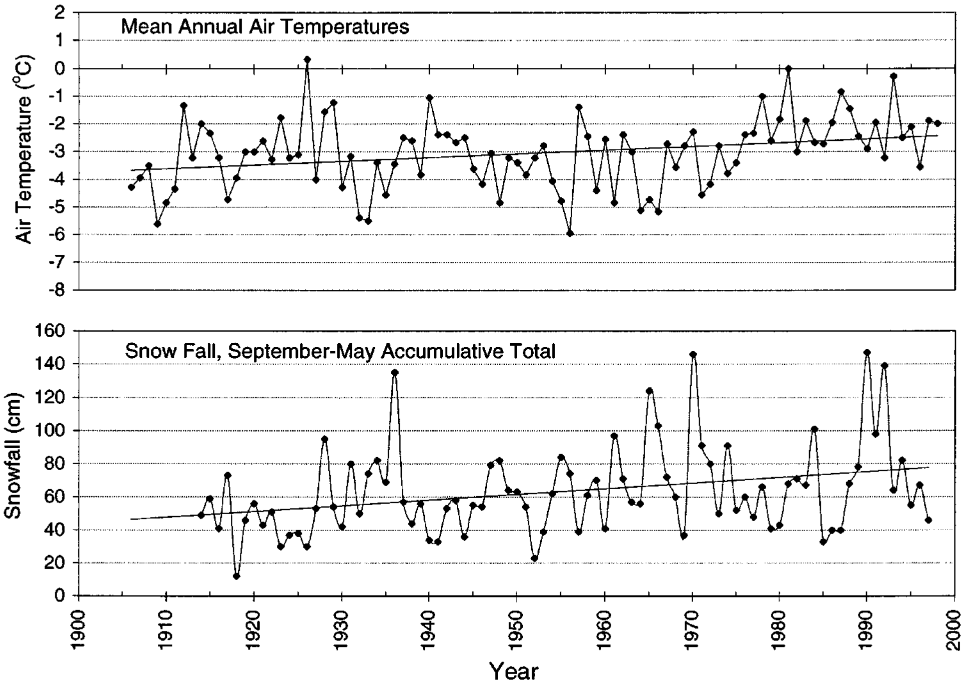

*Figure 10.* Mean annual air temperatures (1906–1998) and winter accumulative snowfalls (1914–1998) for Fairbanks, Alask (from ACRC, 1999). Trendlines based on linear regression.

depths have increased since the early 1900s. The long-term trend established by linear regression indicates snowfall has increased 42% over this period.

Over a longer period, the paleoclimatic record generated for the last four centuries in the circum-Arctic region (Overpeck et al., 1997) and North America (D'Arrigo and Jacoby, 1993), indicates that temperatures were relatively cold before ~1730, warm from ~1730–1810, reached their coldest temperatures during the last 400 years at ~1840, rapidly warmed from 1850–1960, cooled during the mid-1960s and early 1970s, and warmed again during the 1980s (Figure 11). Since the Little Ice Age (ending ~1850), climate has warmed 1–3 °C locally, and 1.5 °C across the Arctic. Note also that the proxy record indicates temperatures generally were warmer during the 1700s in comparison to the 1800s. A more recent reconstruction of annual temperatures in the northern hemisphere by Mann et al. (1998) also supports these trends.

Climatic warming also is revealed in permafrost temperatures. Permafrost temperatures measured in boreholes in northern Alaska have increased 2–4 °C during the last 50–100 y (Lachenbruch and Marshall, 1986). In central Alaska, borehole monitoring by Osterkamp and Romanovsky (1999) reveal that temperatures in discontinuous permafrost have warmed up to 1.5 °C since the mid-1980s.

The current trend in climatic warming is likely to continue according to general circulation models that incorporate climatic responses to increased atmospheric

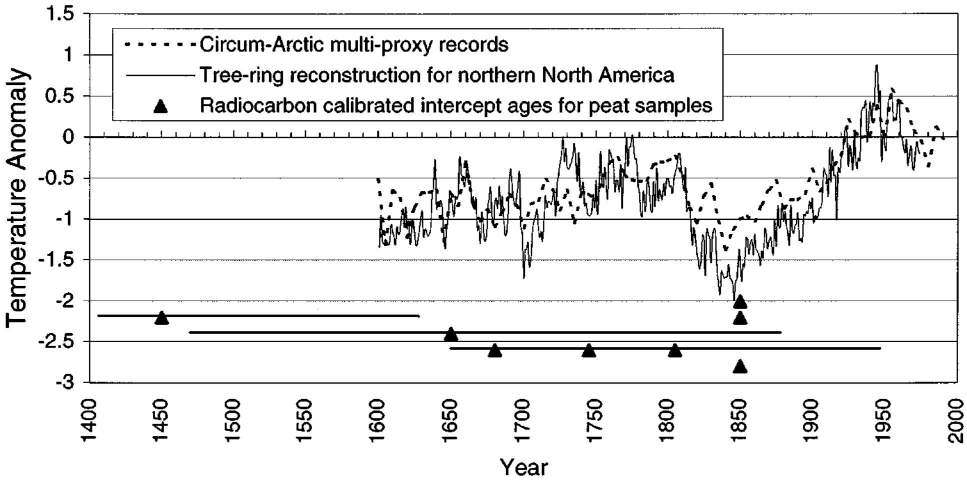

*Figure 11.* Reconstruction of North American summer temperatures were based on tree-ring analysis (D'Arrigo and Jacoby, 1993) and Arctic-wide summer-weighted annual temperatures were based on multiple standardized proxy indicators (Overpeck et al., 1997). Radiocarbon dates (calibrated intercepts) are provided for peat samples used to date onset of degradation in collapse-scar fens and bogs (see Table II). Horizontal bars associated with intercept dates denote calibrated age ranges (95% probability) and one sample had multiple calibrated intercepts. Vertical positions of radiocarbon dates are not related to temperatures.

concentrations of greenhouse gasses (Houghton et al., 1996). Simulations have predicted a global warming of 2–3 °C in response to atmospheric trace gases, and warming in northern latitudes may be as much as 4–6 °C (Houghton et al., 1996). While there are deficiencies in the ability of the general circulation models to incorporate arctic climatic characteristics, higher-resolution models coupling atmospheric-ice-ocean conditions are being developed that should aid prediction of future climatic changes in Alaska (Lynch et al., 1995).

## 5. Discussion

### 5.1. ECOLOGICAL CONSEQUENCES AND EXTENT

Permafrost degradation on the ice-rich lowlands on the Tanana Flats is leading to radical restructuring of ecosystem patterns and processes associated with widespread death of birch forests and their replacement by herbaceous aquatic ecosystems. Changes include alterations from precipitation- to groundwater-driven wetlands, increased organic-matter accumulation under saturated soil conditions, and complete alteration of species from tree- and shrub-dominated forests to herb- and sedge-dominated fens. We have not studied the successional sequence after fen development, but we have observed a few instances of the development of shrub-rich fens (mostly *Myrica gale* and *Chamaedaphne calyculata*) and colonization of tamarack (*Larix laricina*). In comparison, fire also was a widespread disturbance that affects both upland and lowland areas, but fire alone does not cause such irreversible changes in ecosystem properties. Usually, vegetation recovers its forest structure and species composition within 30–50 years, although it may take 100–200 years for a needleleaf canopy to become dominant again (Foote, 1983; Van Cleve and Viereck, 1983).

The dominant ecological pathway of lowland birch forests being converted to lowland fen meadows and the close spatial association of forests with fens indicates a close hydrologic and geomorphic linkage between these ecosystems. Birch forests presumably developed where they did because early permafrost aggradation (with high ice content) lifted the permafrost plateaus above the surrounding terrain. The layered ice structures suggest that groundwater movement to the freezing front was integral to the development of thick ice sequences. Soil drainage, which facilitates slightly better soil aeration for the growth of birch trees, is aided by both the heaving of the ground surface under the birch and by the lowering of the regional water table by the collapse-scar fens. In turn, the fens only develop where birch forests existed because the permafrost there was ice-rich with high thaw-settlement potential.

In contrast, the lowland black spruce forests were usually stable in terms of thermokarst. In all the black spruce sites from which we have taken deep soil cores, the permafrost had little excess ice and thermokarst features were uncommon at the surface. In addition, our limited monitoring of soil temperatures indicates permafrost temperatures under black spruce are slightly colder than under birch forests. While we are aware that black spruce forests can be associated with permafrost with high ice content in interior Alaska (Osterkamp et al., 2000), we have not observed it in our study area.

The rate and extent of permafrost degradation on the Tanana Flats is unusual in comparison with most areas in central Alaska, although similar processes have been observed in other (e.g., Mentasta, Nowitna lowlands, Innoko lowlands) isolated lowland areas (Osterkamp et al., 2000). We attribute the rapid degradation rate in part to the extensive groundwater movement through the fens and underlying outwash gravel on the Tanana Flats. In contrast, the relative stability of permafrost under undisturbed black spruce (albeit black spruce forests are highly susceptible to fire and associated changes in the microclimate), indicate that we should be cautious in extrapolating the rate and extent of permafrost degradation occurring on the Tanana Flats across subarctic Alaska. Furthermore, thermokarst is limited to ice-rich conditions, which are prevalent in fine-grained lowland deposits, and is not as common in permafrost areas on uplands, which tend to be better drained and underlain by bedrock.

### 5.2. RESPONSE TO CLIMATIC CHANGE

The occurrence of widespread thermokarst during a period when the climate was warmer during the 1700s and 1900s does not necessarily prove causation. Numerous environmental factors contribute to permafrost formation and degradation including air temperatures, snow depth, vegetation canopy, soil texture and moisture, organic accumulation, hydrologic movement, and disturbance by fire or man. In the following discussion, we review field studies and simulations that analyze the response of permafrost to changes in air temperatures and discuss other environmental factors that can contribute to permafrost degradation. We then use this circumstantial evidence to evaluate the role of climatic warming in thermokarst development.

Field studies and modeling both indicate that permafrost degradation is sensitive to climatic changes of the magnitude that have occurred during the last 150 y. Halsey et al. (1995) found that the extent of permafrost in bogs was highly correlated to mean annual temperature. Analyses of differences in landform distribution in Canada by Vitt et al. (1994) indicate that permafrost is sensitive to changes in mean annual temperature of only 1 °C. Federov (1996) showed that permafrost stability in central Sakha was sensitive to summer air temperatures and noted three main periods of cryological stress between 1931 and 1991, the late 1930s, mid-1940s to mid-1950s, the late 1970s to early 1990s. Simulations of changes in permafrost distribution in response to changes in air temperatures indicate that the zone of discontinuous permafrost would be reduced 24–28% by an increase of 2 °C (Anisimov and Nelson, 1996), although the regional patterns differ substantially (Anisimov and Nelson, 1997). Simulations by Jorgenson and Krieg (1988) for hilly terrain near Fairbanks, indicate that permafrost extent would be reduced from 51% to 37% of the area by an increase in mean annual air temperatures from –5 °C to –3.5 °C.

Three major factors complicating the relationship between climatic warming and permafrost degradation, however, are the role of winter snow cover, wildfires, and groundwater movement. Numerical simulations have shown that soil temperatures are strongly affected by snow depth and density (Goodrich, 1982; Riseborough and Smith, 1993). Similarly, field studies have shown a strong relationship between snow cover and permafrost and variation in snow cover is the principal factor controlling permafrost distribution in areas near the southern margin of the permafrost zone (Brown, 1973; Smith, 1975; Lévesque et al., 1998). In numerical simulations of climatic effects on ground temperatures using a calibrated model at a site only 10 km from our study area, Osterkamp and Romanovsky (1999) showed that the permafrost has warmed since 1970 as a result of changes in air temperatures and snow cover. During the late 1980s and early 1990s the warming was attributed to increased snow depths rather than warmer air temperatures. In contrast, Burn (1998b) found decreasing snow depths and permafrost temperatures during the 1990s, indicating that there is substantial regional variation. We suggest that the increase of snow depths that has accompanied the increase in air temperatures in central Alaska (Figure 10) during the last century has contributed to permafrost degradation.

Fire influences permafrost dynamics because it can burn off the plant canopy, and remove a substantial portion of the organic layer, which increases soil temperature and thus leads to permafrost degradation (Viereck, 1973; Swanson, 1996; Burn, 1998b). In late-successional stages permafrost reestablishes, resulting in a cycle of aggradation and degradation (Viereck, 1973; Zoltai, 1993). In the nearby Porcupine River drainage, Yarie (1981) estimated fire frequency to be 48 y. Between 1950 and 1998, ∼30% of Fort Wainwright was affected by fires (Jorgenson et al., 1999), while tree ages in both the birch and black spruce forests indicate the last fire in our intensive study area was around 1930.

Although fires can initiate permafrost degradation, it does not appear that fire is the principal cause of degradation in the study area because we observed numerous locations where permafrost did not degrade after fire, and there was little correspondence between fire occurrences and permafrost degradation (Jorgenson et al., 1999). Indeed, permafrost would be rare in central Alaska if permafrost always was degraded by fire, given the high frequency of fires. The role of fire is further complicated by the linkage between air temperatures and fires; fires are more prevalent in warmer and drier weather and increasing air temperatures should increase the frequency and magnitude of fires (Juday et al., 1998). This linkage may help accelerate permafrost degradation under a warming climate.

The effects of groundwater on permafrost stability are not well known. Kreig and Reger (1982) found that presence of groundwater complicated the analysis of permafrost distribution in abandoned floodplains in the discontinuous zone. Intensive geophysical investigations of the hydrogeology in the abandoned floodplain adjacent to the Chena River by Lawson et al. (1996) found the distribution of groundwater above, below, and within the discontinuous permafrost to be extremely complex. Similarly, the Tanana Flats is a large area of groundwater discharge with complex patterns (Racine and Walters, 1994). Heat from this groundwater may contribute to the permafrost degradation because the groundwater is relatively warm (2–4 °C) year-round, surfaces in numerous places across the flats, and contributes to water moving through the moats along the collapsing margins of the birch forests. Near-surface groundwater movement also may be linked to climate because of increased precipitation and increased development of channels through the degrading permafrost.

While the above-mentioned factors influence permafrost temperatures and stability, our results indicate that the development of thermokarst on the Tanana Flats is associated with the climatic warming that began in the mid-1700s. The low accuracy of our techniques for dating does not allow us to confidently identify the date of initiation of thermokarst, but the evidence indicates that nearly all the degradation has occurred since ∼1750 and that 83% of the degradation occurred before 1949. While much of this degradation may have occurred during the period of rapid warming in the late 1800s and early to mid-1900s, it was not possible to determine degradation rates during this period. That this degradation coincided with a period of dramatic climatic warming, indicates a causal relationship. Additional support for a causal relationship is provided by the widespread occurrence of thermokarst across both Alaska and Canada during the last one to two centuries, which only a regional factor such as climate can explain. Throughout this period degradation would have been enhanced by increased snow depths, fires, and groundwater movement, which are directly or indirectly linked to increased air temperatures. It is not possible, however, to evaluate their relative contribution.

### 5.3. IMPLICATION FOR GLOBAL CLIMATE SYSTEM

Permafrost degradation may have important implications for the global climate system from feedbacks involving both carbon sequestration and methane production. Permafrost degradation is commonly viewed as causing a thickening of the active layer, which in turn enhances mineralization of carbon stored in the permafrost (Billings, 1987, Nelson et al., 1993). On the Tanana Flats, however, organic-matter accumulation (mostly live material) is much thicker in the newly developed bogs and fens (Racine et al., 1998), indicating carbon accumulation in the semi-aquatic ecosystems can be relatively rapid. Thus, permafrost degradation may enhance carbon sequestration, rather than promote carbon losses, at least in low-lying, ice-rich areas.

Methane production likely will be increased by permafrost degradation. Moosavi et al. (1996) measured methane fluxes up to three orders of magnitude higher in bog meadows than in black spruce-low scrub. Funk et al. (1994) found that water depths were by far the largest factor affecting methane emission, indicating that fen formation should have significant effects on regional methane production. While the amount of methane locked in permafrost can be substantial (Lorenson et al., 1992; Kvenvolden et al., 1992), more information is needed on the relative contribution of methane produced from newly released organics versus that from newly sequestered carbon in collapse-scar bogs and fens. These observations on the potential contribution of permafrost degradation to global climatic feedbacks (also noted by Camill and Clark, 1998) indicate that changes in carbon dioxide and methane emissions are more complicated than those associated with the simple concept of decomposition of carbon stored in the permafrost.

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