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The Areal Pattern of Burned Tree Vegetation in the Subarctic Region of Northwestern Canada

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ABSTRACT. Vegetation and terrain analyses of 1312 air photos spanning the subarctic, low arctic, and portions of the adjacent high boreal region of northwestern Canada permitted geographic characterization of the areal pattern of burned forest and forest-tundra vegetation. In terms of its lower areal extent of burns, and lower frequency of air photos showing burns, the forest-tundra is distinct from both open crown and closed crown forest regions. Burns show a general decrease in areal coverage from the northwest (Mackenzie River to Great Bear Lake: 0-50% of the terrain) to the southeast (Great Slave Lake to Hudson Bay: 0-10%). In the northwest, the flat till plains, high cover of continuous mature forest, and scarcity of lakes, coupled with dominance of slowly regenerating white spruce (in the forest-tundra) may help to account for the extensive burned vegetation. In the eastern half of the study region, the northern limit of burns normally does not extend beyond the line where tree cover equals upland tundra cover. In this eastern sub-region, tree cover decreases rapidly northward within the southern half of the forest-tundra, constraining the areal extent of individual burns. Burns extend about 25-75 km into the forest-tundra, decreasing in areal coverage with distance east of Great Slave Lake. Burn cover in the forest-tundra north of Great Slave Lake generally exceeds that east of Great Slave Lake. Weather patterns and an abundance of lakes may help to account for the lower cover of burns east of Great Slave Lake. Burns north of Great Slave Lake peak in cover in the low Subarctic along a NW-SE axis that lies NE of high fire risk and occurrence zones. Strong correlations were observed between burn cover and upland tundra cover (−r) and between burn cover and the tree:upland tundra cover ratio (+r).

Key words: boreal, climate, fire ecology, Northwest Territories, spruce, Subarctic, vegetation, weather

RÉSUMÉ. Des analyses de la végétation et du terrain faites à partir de 1312 clichés aériens pris en survolant le Subarctique, le bas Arctique et des portions de la région boréale extrême adjacente, dans le nord-ouest du Canada, ont permis de définir géographiquement le schéma de la surface recouverte d'une végétation composée de brûlis et de forêt-toundra. Si l'on considère sa superficie moins étendue recouverte de brûlis et le plus petit nombre de clichés aériens révélant des brûlis, la forêt-toundra est différente des régions boisées à voûte ouverte et de celles à voûte fermée. On constate une diminution générale de la superficie des brûlis en allant du nord-ouest (du Mackenzie au Grand Lac de l'Ours: 0-50 p. cent du terrain) au sud-est (du Grand Lac de l'Esclave à la baie d'Hudson: 0-10 p. cent). Dans le Nord-Ouest, les plaines de till planes, le couvert étendu de forêt évoluée ininterrompue, ainsi que la rareté des lacs, joints à la dominance de l'épinette blanche à lente régénération (dans la forêt-toundra), peuvent expliquer l'importance de la superficie des brûlis. Dans la moitié orientale de la région de l'étude, la limite septentrionale des brûlis ne dépasse généralement pas la ligne où le couvert boisé est égal au couvert de toundra des hautes terres. Dans cette sous-région orientale, le couvert boisé diminue rapidement vers le nord, à l'intérieur de la moitié méridionale de la forêt-toundra, restreignant ainsi la superficie des brûlis individuels. Ceux-ci s'avancent d'environ 25 à 75 km à l'intérieur de la forêt-toundra, diminuant de superficie en s'éloignant du Grand Lac de l'Esclave. Le couvert de brûlis dans la forêt-toundra au nord du Grand Lac de l'Esclave dépasse en général celui situé à l'est de ce lac. Les régimes des pluies et l'abondance des lacs peuvent expliquer la moindre importance du couvert de brûlis à l'est du Grand Lac de l'Esclave. Les brûlis au nord de ce lac atteignent leur superficie maximale dans le Subarctique inférieur le long d'un axe N.O.-S.E. qui se trouve au nord-est de zones à hauts risques et fréquentes occurrences d'incendie. On a observé de fortes corrélations entre le couvert de brûlis et celui de toundra des hautes terres (− r), ainsi qu'entre le couvert de brûlis et le rapport entre le couvert forestier et celui de toundra des hautes terres (+ r).

Mots clés: boréale, climat, écologie du feu, Territoires du Nord-aa-Ouest, épinette, Subarctique, végétation, climat

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INTRODUCTION

The circumpolar taiga, or boreal forest, of which approximately one-third is located in Canada and two-thirds in the U.S.S.R., is one of the most remote forest regions on earth. Settlements and industrial exploitation are common only in the southern and middle portions of the closed coniferous forest. In northwest Canada, the high boreal closed crown, low subarctic open crown, and high subarctic forest-tundra regions form a relatively undisturbed broad vegetation belt lying south of the low arctic tundra region (Rowe, 1972; Ecoregions Working Group, 1989).

Interest in the forest-tundra region in particular has risen recently because predicted climatic change due to greenhouse effects may be first evidenced there (Kellogg and Zhao, 1988). In particular, the Canadian Subarctic may shrink in total area, possibly by 58%, under the northward encroachment of grassland and boreal forest vegetation (Rizzo, 1988). The subarctic forest-tundra is expected to migrate northward, from extremes of 300-400 km in eastern Canada to negligible distances in the far northwest (Zoltai, 1988), where northward movements are constrained by the Arctic Ocean. Vegetation maps depicting contours of percentage of cover for various vegetation types in the Subarctic have been prepared recently (Timoney, 1988) and should prove useful as baseline data in assessing predicted tree line movements.

Vegetation cover patterns within the forest-tundra are influenced by climate and climatic variablility, edaphic and fire patterns, and landscape-climate feedbacks in an environment marginal for both forest and tundra (Timoney, 1988). One of the most important stochastic physical forces that influence northern vegetation is fire, which shows wide annual and decadal variability in area burned. For the years 1950-89 in the Northwest Territories, the annual number of forest fires averaged 204, with a range of 42 (1957) to 613 (1989); the average area burned annually was 3042 km^2 ± 3124 km^2 S.D., with a range of 23.1 km^2 (1965) to 19 891 km^2 (1979) (Murphy *et al.*, 1981; National Research Council of Canada, 1990). These numbers provide only a general guide to fire activity in the forest-tundra zone. In 1980, for

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example, fires burned large tracts of the boreal forest of western Canada, yet few fires occurred in the forest-tundra (Stocks, 1983:Fig. 1).

While upland tundra does burn (Wein, 1976; Payette *et al.*, 1989), tundra burns are difficult to identify on air photos after only a few years of recovery (Cochrane and Rowe, 1969; Wein and Bliss, 1973). These references suggest that tundra fires occur infrequently, at low intensities, and are small in size. With increasing areal cover of trees, fires are more common, larger, and of higher intensity, and the burned areas are recognizable for many years after fire (Rowe *et al.*, 1975).

The areal pattern of burned tree vegetation in the Subarctic and adjacent high boreal of western Canada may be viewed as the integral of terrain and vegetation influences, weather patterns, and post-fire regeneration rates. The balance between post-fire recovery time and annual burn rate determines the areal cover of terrain presently treeless due to fire. While both tree regeneration rates and annual burn rates in the Subarctic decrease generally from SW to NE, regional differences in vegetation, terrain, and weather patterns manifest themselves in marked variability in the areal pattern of burned subarctic tree vegetation.

In this paper we quantify and map the areal cover percentage of burned subarctic tree vegetation in northwestern Canada. Explanations for the geographic variability in the observed burn patterns are offered.

STUDY REGION

The study region spans the subarctic and low arctic vegetation regions from the Yukon-Northwest Territories border west of the Mackenzie Delta southeast to the west coast of Hudson Bay in southern Keewatin and northernmost Manitoba (Fig. 1). Forest fuel types for the forest-tundra are typified by white spruce/shrub/*Dryas*-legumes/ *Carex*/moss in the northwest and black spruce/shrub/ericad/moss in the southeast (Timoney, 1988). In the central forest-tundra, white spruce communities dominate eastward to ~114°W, while black spruce communities dominate farther east (Timoney, 1988). In the open crown and closed crown regions of northwestern Canada, black spruce/shrub/moss woodlands and forests predominate (Black, 1977; Bradley *et al.*, 1982; Ritchie, 1984; Ecoregions Working Group, 1989; among others).

In northwestern Canada, the high boreal closed crown/low subarctic open crown boundary is characterized by a mean annual net radiation (MANR) of 22-27 kcal·cm^{-2}·yr^{-1} and a mean July air temperature (MJAT) of 15°C; the open crown/forest-tundra boundary exhibits an MANR range of 18-23 kcal·cm^{-2}·yr^{-1} and an MJAT of 13°C; the forest-tundra/low arctic tundra boundary is characterized by a MANR of 12-15 kcal·cm^{-2}·yr^{-1} and an MJAT of 10-11°C (Timoney, unpubl. data).

Fire Occurrence and Weather Patterns

The limited number of weather stations in the study region permits only broad generalizations. Fire weather zones described by Simard (1973) approximate the open crown forest and forest-tundra zonation between the Mackenzie valley and the East Arm of Great Slave Lake. East of Great Slave Lake, Fire Weather Index isolines trend more north-south than do the vegetation zones, indicating that the southeastern Subarctic is less fire prone than that north of Great Slave Lake.

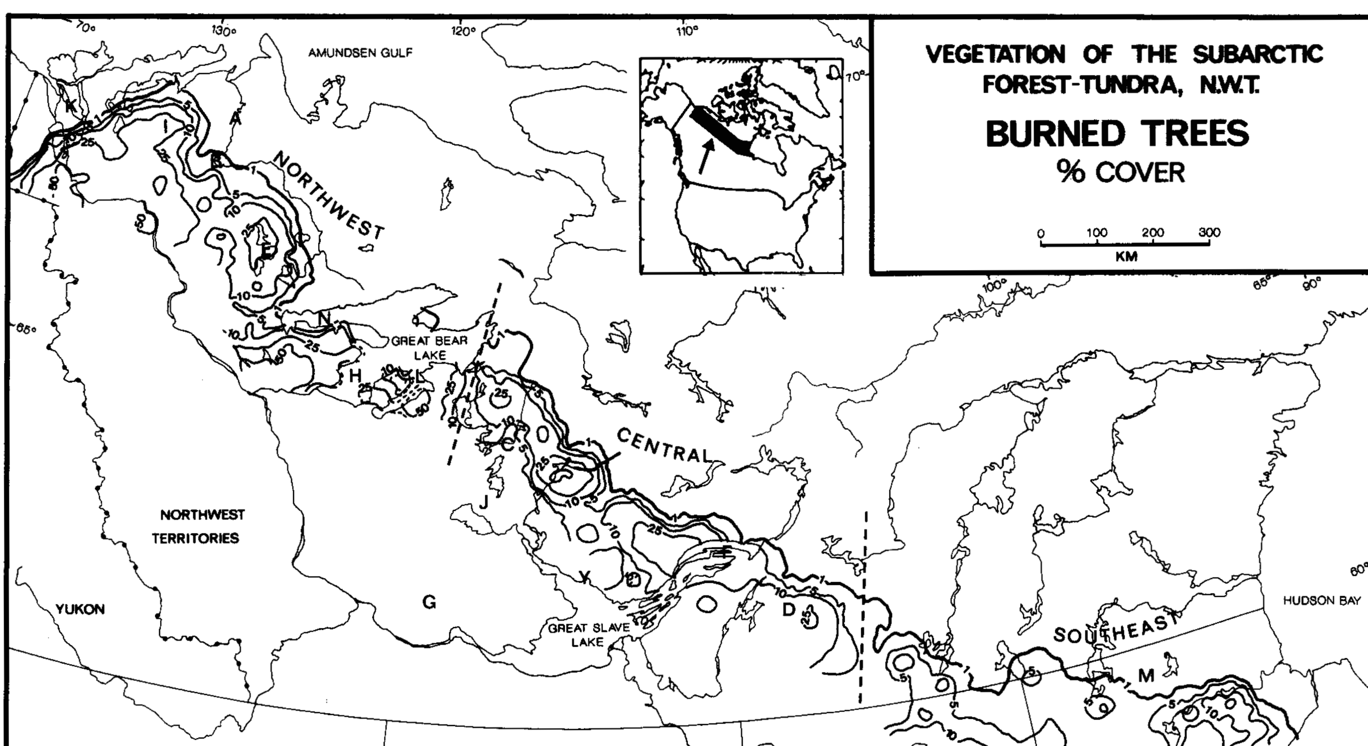

FIG. 1. Areal cover percentage of recently burned tree vegetation in subarctic northwestern Canada. Letters locate place names used in text: a) Anderson River, b) big bend of Anderson River, c) Camsell-Hardisty-Indin lakes, d) Caribou Range, e) Colville Lakes, f) East Arm, g) Horn Plateau, h) Keith Arm, i) Kugaluk River, j) Lac La Martre-Faber lakes, k) Mackenzie Delta, l) McVicar Arm, m) northern Manitoba, n) Smith Arm, y) Yellowknife.

A high fire risk zone along the Shield/Paleozoic boundary NW of Yellowknife has been identified by Rowe *et al.* (1975). There, low pressure systems moving south up the Mackenzie valley apparently interact with high pressure systems moving SE parallel to the tree line. The arctic and Pacific highs, which collide near the southern edge of the forest-tundra in summer, are separated by a trough of low pressure (Rowe *et al.*, 1975). The interaction of these high and low pressure systems leads to air mass instability, thunderstorms, and lightning.

The average Fire Weather Index for the months June, July, and August is moderate for the central forest-tundra, with very low to moderate indices for the forest-tundra of the northwest and southeast (Table 1). A similar pattern is found in the low Subarctic: high Fire Weather Index in the central district and low to moderate indices both in the northwest and southeast.

The average forest fire occurrence for the forest-tundra of western Canada ranges from moderate for the central district between Great Bear and Great Slave lakes to low for the northwest and southeast (Simard, 1975; Table 1). Fire occurrence in the low subarctic open crown region is on the order of 2-4 times greater than in the high Subarctic. The highest fire occurrence is observed in the central district, with lower fire occurrence in the northwest and southeast.

METHODS

A matrix of 1312 National Air Photo Library (Ottawa) black and white air photos was used in the study. Air photos were taken from 1950 to 1980, with 68% taken between 1950 and 1961, at a scale ranging from 1:50 000 to 1:70 000. The total areal coverage approximated 260 000 km^2, or 24% of the study region. Air photos were analyzed at 6× magnification with a stereo-microscope for percentage cover of tree, upland tundra, tall shrub, treeless wetland, and burned tree vegetation, rockland, water, and unsuitable (due to photo quality). Parent materials, surficial features, bedrock types; mean, maximum, and minimum elevations and relief; and longitude and latitude of photo centers were recorded. Cover percentages were adjusted to percentage of land surface by algorithms correcting for percentage of water and unsuitable (due to clouds, poor focus, etc.). Photo positions were transformed to a Lambert conformal map projection and the air photo data then was passed to Surface II software (Sampson, 1978).

The functional criteria used to delimit the vegetation regions in this study were: 1) closed crown/open crown boundary = southern limit (<0.1% cover) of open crown conifer forest on well-drained uplands; 2) open crown/forest-tundra boundary = southern limit (<0.1% cover) of upland tundra; 3) forest-tundra/low arctic tundra boundary = northern limit (<0.1% cover) of trees (≥3-4 m height) (see Timoney, 1988:Appendix 7, for details and synonymy).

Burned subarctic and high boreal lands fell into three main vegetation types: tree, peat plateau, and upland tundra. Only recently burned trees were placed in a separate category and they are the subject of this paper. Burned peatlands and upland tundra were included under their respective types (see Timoney, 1988).

Recently burned forests and peatlands were readily identified through comparison with unburned areas. In what were densely treed stands, recent burns were characterized by a lighter tone and a change from stippled to grainy texture. Lacking clear tonal and textural differences and burn lines, comparison of suspected burned terrain with that on islands and peninsulas was helpful. Burns of sparsely treed forest-tundra stands were typically darker toned than adjoining unburned areas. This is especially true in the northwest, where lichens are replaced after fire with darker-toned shrubs.

Burned peat plateaus, with dark-toned exposed peats and shrubs, contrasted sharply with unburned, light-toned *Cladonia*-covered peat plateaus. Most difficult to discern were burned upland tundras of the northwest. There, reference to pre- and post-fire photos, or to low-level (large-scale) photos or ground truth, was often needed. The most obvious air photo differences were a change from light (tonal scale N7) to medium gray (N5) and the presence of distinct burn lines.

Due to the spatial and temporal variability of fire, areal burn cover tended to vary widely, requiring more averaging (eight neighbor air photos; Fig. 1) than other vegetation/landscape types (4-6 photos) in order to depict regional patterns. The figure depicts the percentage cover of recently burned (in most cases <25 years old) tree vegetation; burned upland tundras, shrublands, and wetlands (e.g., peat plateaus) are excluded. Old or light burns, which showed evidence of fire but were currently treed, were not classified as burn. In areas of slow tree regeneration or dysclimax, old burns would be classed as "recent" burn.

The northernmost bold line in Figure 1 depicts the approximate northern limit of burns (the 1% contour). A zero contour could not be used, as averaging with eight neighbor photos "pulled" the contour line northward, resulting in error. Northward of the bold line, <1% of the landscape was covered by recent burn.

Rank correlations (Spearman's rho) of burn cover data were done on four data sets: 1) all air photos (n=1312); 2) subset of open crown and closed crown forest photos, exclusive of those contiguous with the forest-tundra (n=300); 3) air photos with burn percentage cover > 0, plus 19 randomly chosen air photos with zero burn cover (n=246; value of 19 was reached by referring to a burn cover/air photo

TABLE 1. Forest fire occurrence (after Simard, 1975) and Fire Weather Index (average FWI for June, July, August, after Simard, 1973) for the high subarctic forest-tundra (FTU) and low subarctic open crown forest (OCF) regions of western Canada, as interpolated from Timoney (1988)

	Northwest		Central		Southeast	
	FTU	OCF	FTU	OCF	FTU	OCF
# fires per 1000 km^{-2}·yr^{-1}	.00-.20	.10-.40	.00-.40	.04-1.50	.00-.20	.04-.75
Fire Weather Index	2-8 (very low to moderate)	5-8 (low to moderate)	6-10 (moderate)	10-14 (high)	2-9 (very low to moderate)	5-10 (low to moderate)

frequency table and histogram for the full data set); 4) subset of air photos with burn percentage cover > 0 (n=227).

Vascular plant nomenclature follows Porsild and Cody (1980). Place names used in the text are plotted in Figure 1.

RESULTS AND DISCUSSION

Correlations of Vegetation and Terrain Factors with Burned Tree Vegetation

Descriptive statistics (Table 2) indicated that the untransformed vegetation cover and terrain variables were all non-normal in distribution. Percentage cover of burned tree, water, rockland, tall shrub, wetland, and relief were strongly leptokurtic and positively skewed; tree and upland tundra cover were bimodal (platykurtic) and weakly skewed; the ratio of tree + burned tree:upland tundra cover was positvely skewed. Attempts at normalizing the data via transformation met with limited success. The only successful transformations were root, ranging from $x^{-0.34}$ to $x^{-0.40}$. Therefore, non-parametric statistics were used on untransformed data to test the relationships of percentage of burn cover with vegetation and terrain variables.

As a whole, the strongest correlates of burned tree cover were tree and tundra cover (Table 3). Burn cover was positively correlated with actual (observed) tree cover for the full data set, indicating that burned tree cover increases southward through the forest-tundra into the open crown forest. The data subsets showed strong negative correlations between burn and actual tree cover, a relationship due simply to killing of trees by fire.

Both upland tundra (−r) and the tree:upland tundra cover ratio (+r) were strongly correlated with burns. Such correlations might reflect upland tundra vegetation acting as firebreaks and/or be due to pre-emption (i.e., upland tundra cover is negatively correlated with burned forest simply by pre-empting the landscape of forest cover). The latter possibility was investigated by adjusting burn cover for the percentage of the landscape covered by upland tundra: $\%\ \mathrm{burn}_{(adjusted)} = (\%\mathrm{burn}/(100-\%\mathrm{upland\ tundra})\cdot 100)$. Adjusted burn cover was ranked and correlated with ranked upland tundra cover ($r=-.498$, $p<.001$, $n=1312$) and ranked tree:upland tundra ratio ($r=.530$, $p<.001$). As the correlation remained highly significant, it is likely that upland tundra restricts burn cover through its sparse and discontinuous fuel. Lichen-dominated tundra in northern Quebec is believed instrumental in limiting the spread of fire (Payette *et al.*, 1989).

Correlations with other vegetation variables were weaker. In the closed crown/open crown forest subset, tall shrub was negatively correlated with burn, perhaps indicating that moist shrub communities also act as firebreaks. Wetland was negatively correlated with burn in the full data set and non-significant in the data subsets.

Of the terrain variables, both rockland (semi-barren bedrock) and water were negatively correlated with burn. An increase in percentage cover of either rockland or water increases the discontinuity of forest fuel. The lack of correlation between burn and water cover in the full data set may be due to the preponderance of zero burn values in the northern forest-tundra and low arctic tundra. Conversely, the lack of burn/water correlation in the smallest data set (n=227, burn >0.0%) appears to be related to the exclusion of zero burn values. The positive correlation between relief and burn, albeit weak, may mean that better drained hilly terrain is more fire prone than flat terrain.

Area Burned and Frequency of Air Photos with Burns by Vegetation Region

Burned tree vegetation reached its highest landscape cover and air photo frequency (# photos with burn >0%/total photos) in the open crown forest, lowest cover and frequency in the forest-tundra, and was intermediate in cover and frequency in the closed crown forest region (Table 4). Area of burn was not significantly different, however, between the open and closed crown forest regions ($p = .277$; Table 5); nor was burn frequency ($p \simeq .4$; Table 6). Area of burn and frequency on air photos were significantly higher in the closed crown forest (both $p<.00001$) and in the open crown forest (both $p<.00001$), as compared to the forest-tundra (Tables 5-6). In terms of area burned and frequency of air photos with burns, the forest-tundra must be viewed as distinct from both the open crown and closed crown vegetation regions.

The Areal Pattern of Burned Tree Vegetation

The areal pattern of burned tree vegetation in subarctic-high boreal western Canada may be divided on the basis of burn cover into three sub-regions: 1) medium to high burn

TABLE 2. Descriptive statistics for the vegetation and terrain variables of the full data set (n=1312 photographs)

	Mean	Median	S.D.*	S.E.*	Kurtosis	Skewness
Burned trees	5.1	0.0	15.1	0.4	11.5	3.4
Water	14.0	10.0	11.1	0.3	2.6	1.4
Rockland	3.4	0.0	8.3	0.2	23.2	4.2
Tree	31.2	11.4	35.0	1.0	−1.3	0.6
Upland tundra	47.0	56.6	38.9	1.1	−1.7	−0.1
Tall shrub	5.2	3.5	6.9	0.2	39.6	5.0
Wetland	11.0	6.1	15.4	0.4	13.4	3.5
T:UTU*	20133.2	0.3	36759.4	1014.9	−0.2	1.3
Relief* (m)	72.9	54.3	75.1	2.1	36.5	4.7

*Abbreviations: S.D. = standard deviation; S.E. = standard error; T:UTU = tree (observed+burned tree):upland tundra cover ratio; Relief = relief (m) on an air photo. All non-transformed variables are non-normal ($p<0.001$, Kolmogorov-Smirnov test, 2-tailed p).

TABLE 3. Rank correlations (Spearman's rho) of percentage of burn cover with vegetation and terrain variables for the four data sets (statistical significance: ^ $p<0.001$; ** $p<0.01$; * $p<0.05$)

Data set (n)	Tree	Upland tundra	T:UTU#	Tall shrub	Wetland	Rockland	Water	Relief
1312	.328^	−.500^	.532^	.071*	−.265^	−.113^	−.053	.090**
300	−.777^	—	—	−.260^	−.079	−.214^	−.271^	.108
246	−.694^	−.238^	.252^	−.043	−.101	−.011	−.136*	.059
227	−.872^	−.133*	.144*	−.010	−.029	.061	−.100	.052

T:UTU = tree (observed+burned tree):upland tundra cover ratio.

TABLE 4. Percentage cover of burned trees by vegetation region*

	Mean	Med.	S.D.	S.E.	Kurt.	Skew.	n	n_{burn}	f_{burn}
Closed crown	14.9	0.0	23.4	2.7	1.6	1.6	75	35	46.66
Open crown	17.5	3.8	24.7	1.6	0.5	1.3	247	134	54.25
Forest-tundra	1.7	0.0	8.2	0.3	33.6	5.6	700	58	8.29

*n_{burn} = number of air photos with burn > 0.0% by region; f_{burn} = %frequency of air photos with burn > 0.0% by vegetation region.

TABLE 5. Tests of percentage cover of burned trees by vegetation region (Mann-Whitney U test, m.r. = mean rank; Z and 2-tailed p values corrected for ties)

	Closed crown	Open crown
Open crown forest	m.r. CCF 151.8 m.r. OCF 164.4 n=322; Z -1.086 p = 0.277	—
Forest-tundra	m.r. CCF 525.9 m.r. FTU 373.2 n=775; Z -9.944 p < 0.00001	m.r. OCF 639.4 m.r. FTU 415.6 n=947; Z -15.737 p < 0.00001

TABLE 6. Tests of percentage of air photos showing burns by vegetation region (χ^2 test)

	Closed crown	Open crown
Open crown forest	χ^2=0.6296 n=322; 1 d.f. p = ~0.4	—
Forest-tundra	χ^2=83.158 n=775; 1 d.f. p < 0.00001	χ^2=190.249 n=947; 1 d.f. p < 0.00001

cover in the northwest, extending SE from the Yukon border to the south shore of Great Bear Lake; 2) low to medium cover in the central district, extending from Great Bear Lake to about 180 km SE of Great Slave Lake; and 3) low cover in the southeast, extending from SE of Great Slave Lake to Hudson Bay in southern Keewatin and northern Manitoba (Fig. 1).

The Northwest: Burns reach their highest cover and greatest extent in the northwest. The largest area of high burn cover extends SE of the Mackenzie River to the Colville Lakes. In the low Subarctic, 10-50% of the landscape is burned. In the forest-tundra, burn area ranges from 0 to 25%, with the northern limit of burn approaching the limit of trees between the Mackenzie and Kugaluk rivers. The northern limit of burned trees reaches the big bend of the Anderson River, then parallels the Anderson southward to Smith Arm of Great Bear Lake. Areas of >25% burn are found in the Colville Lakes area SW of the Anderson River. Extensive burns are found in the flat terrain west of Keith Arm (Great Bear Lake), and burn cover remains high along the south shore of McVicar Arm (GBL), eastward to the Shield/Paleozoic boundary (10-50%).

Fire weather and fire occurrence, as described by Simard (1973, 1975), do not account for the extensive burned landscape in the northwest. A number of factors may play a role: 1) Recent data from lightning location equipment indicate many lightning strikes in midsummer; continuous sunshine around the summer solstice contributes to the spread of fire (R.P. Bailey and R.A. Lanoville, pers. comm. 1990). 2) The continuity of low subarctic forests, particularly low subarctic black spruce/heath shrub/lichen, may contribute to the great extent of burns in the northwest (Rowe *et al.*, 1974; Black, 1977). 3) In the high subarctic forest-tundra of the northwest, tree cover characteristically remains high to near the limit of trees and thus provides relatively continuous flammable vegetation. 4) Large fires may be favored by the topographic uniformity of the extensive till plains (Rowe *et al.*, 1974) and by the scarcity of lakes, which act as fire breaks. The most extensive burned terrain is found where cover of water bodies is lowest (0 to <10% water). 5) Vascular plant and bryophyte cover is likely higher in forest-tundra plant communities in the northwest than on the Shield (Robinson *et al.*, 1989), as is the percentage of organic carbon in LFH horizons (Timoney and Zoltai, unpubl. ms.). Organic mats are likely thicker and more continuous in the northwest than on the Shield, and these fuel factors together might act to favor spread of fire. 6) White spruce regenerates poorly after fire near its northern limit largely because it does not retain a seed supply in the crown, as does black spruce (Rowe, 1970; Zoltai and Pettapiece, 1973; Ritchie, 1984).

The Central District: Between Great Bear Lake and the East Arm of Great Slave Lake, forest-tundra burn cover ranges from 0 to 10%. In the central low Subarctic, high burn cover (10-50%) extends NW from Indin Lake to Great Bear Lake (east of the Shield/Paleozoic boundary) and NW and SW of the East Arm, Great Slave Lake (Fig. 1).

A belt of high burn cover (10-50%) NE of the Shield/Paleozoic border in the low Subarctic falls off both to NE (forest-tundra) and SW (high boreal). These results are supported by low-level aerial surveys in the low subarctic Camsell-Hardisty-Indin lakes area in this central district, where Kelsall (1960) calculated burned forest cover at 22% of the landscape.

Further corroboration of this belt of high cover of burn is provided by fire management maps (for the years 1967-79, K. MacInnes, DIAND, undated) of the area N and NW of Yellowknife. For the area lying between 114-116°W and 62-66°N, high cover of burn occupies a belt lying between 62°50′ and 64°25′N. In the Lac La Martre-Faber Lake area, DIAND fire maps indicate that percentage cover of burn rises to the NE, as the belt of high cover of burn identified in this study is approached.

Maps of fire weather and fire occurrence (Simard, 1973, 1975), burn cover (DIAND, undated; Kelsall, 1960), and the fire risk zone of Rowe *et al.* (1975) parallel the belt of high cover of burned trees lying NW of Yellowknife. High fire occurrence and fire weather risk evidently occupy a band SW of the peak burn cover in Figure 1. The discrepancy between Figure 1 and other accounts may reflect the offsetting factors of high fire occurrence southward and longer recovery time northward.

Burn cover in the forest-tundra of the central district (0-10%) north of Great Slave Lake generally exceeds that east of Great Slave Lake (0-5%). Aside from weather patterns in the central district that are conducive to forest fires, a contributing factor may be cover of lakes. Water bodies cover 10-25% of the forest-tundra north of Great Slave Lake, averaging about 15%. In contrast, water cover east of Great Slave Lake ranges from 10 to 50%, with an average near 20%.

The Southeast: In the southeast, area burned rarely exceeds 10% of the landscape (Fig. 1). The approximate northern limit of burns generally extends only 25-75 km into the forest-tundra. In the eastern half of the study region, tree cover usually drops rapidly within the southern half of the forest-tundra (Timoney, 1988), constraining burn to low cover values. In general, the northern limit of burns does not extend beyond the line where tree cover equals upland tundra cover.

In the low subarctic Caribou Range (S and SE of Great Slave Lake), burn cover is at a maximum (50%) where water cover reaches a minimum (≤10%). In contrast, the forest-tundra SE and east of Great Slave Lake is comparatively burn free (0-5%). As in the area north of Great Slave Lake, burns extend about 25-75 km into the forest-tundra east of Great Slave, but average burn cover is lower and the limit of burns lies generally closer to the southern edge of the forest-tundra (Fig. 1). In the extreme southeast, burn cover in the low subarctic of northern Manitoba rises (up to 25%); there water bodies cover only 2-10% of the landscape.

Vegetation Influences

The balance between yearly burn and recovery time determines the amount of the landscape currently treeless due to burn. Post-fire recovery times for tree vegetation vary by bioclimatic region and by vegetation type. In the low subarctic open crown region, tree stands may remain shrub-dominated for 25-50 years after fire; high canopy cover is reached in about 50 years; and climax is approximated in 150-200 years (Kershaw *et al.*, 1975; Wein, 1975; Kershaw and Rouse, 1976; Johnson and Rowe, 1977; Black and Bliss, 1978). In contrast, burns in the high subarctic forest-tundra may remain shrub dominated indefinitely (fire-induced "tundras"); regeneration times may exceed 50 years; and climax is approximated in 200-250 years. Fire-induced "tundra" has been observed in the Horn Plateau near Ft. Simpson, N.W.T. (Rowe and Scotter, 1973), in northern Manitoba (Ritchie, 1960), northern Quebec (Payette, 1983; Payette and Gagnon, 1985), Fennoscandia (Hustich, 1966), and elsewhere across the circumpolar Subarctic.

Since climatically driven afforestation is probably more rapid a process than deforestation (in the absence of fire), the forest-tundra should support, on average, more tree vegetation than the current climate sanctions. Thus, the overall effect of fire should be to bring the tree:tundra vegetation ratio closer to equilibrium with climate. Although fires are rarer in the forest-tundra than in the low subarctic and boreal regions, unsuccessful regeneration might locally shift the tree limit south of the climatic potential of adult trees and into equilibrium with seed production and seedling establishment potential.

In extensive burns, such as in the northwest (Zoltai and Pettapiece, 1973; Ritchie, 1984; among others), it is possible that bioclimatic feedbacks (Hare and Ritchie, 1972) with persistent post-fire willow-dwarf birch-green alder vegetation act to reinforce the pseudo-tundra dominance. Persistence of shrub-dominated stands in the northwest also may be related to improved water and nutrient availability on fine-textured tills, resulting in luxuriant growth (Black and Bliss, 1978). Persistence of shrub dominance in the forest-tundra is also related to slow tree growth in that many years elapse before spruce or larch achieve tree size. The lack of a mineral seed bed in areas with deep organic mats may further delay tree establishment and growth rates.

Black spruce, which produces cones at an early age and retains many unopened cones on the tree, is well adapted to fire (Rowe, 1970; Payette *et al.*, 1982). White spruce sheds its annual seed crop prior to formation of new cones such that immature seeds are present on the trees at the time of summer fires. Thus the white-spruce-dominated forest-tundra of the northwest may be susceptible to rapid and persistent depression of potential tree cover.

Seeding from cones retained on fire-killed black spruce must take place within 1-8 years after fire, as the seeds lose their viability with time (Black, 1977). Buried black spruce and larch seed populations in the Subarctic are evidently non-viable (Johnson, 1975; Black, 1977; Payette *et al.*, 1982), making reseeding of burned areas from within a stand subject to time constraints.

Isolated tree stands are relatively fire protected by virtue of their discontinuous fuel source; yet once ignited by a chance lightning strike, they are at risk of extinction in proportion to their isolation from seed sources. Seeding from outside the burn is subject to the vagaries of patch or "island" size, viable seed production, dispersal, and successful establishment.

Burn Cover in Northwestern Canada Relative to That in Northern Quebec

Payette *et al.* (1989:Table 2) studied the fire history of a 54 000 km^2 area in northern Quebec. If we assume post-fire regeneration rates (beyond the shrub stage) of 50 years for the forest-tundra and 37.5 years for the open crown forest (northern boreal forest of Payette *et al.*) and use a 30-year, 1950-79, data window, their burned area occupies 26% of the forest-tundra and 20% of the open crown forest regions. The open crown forest of northwestern Canada averages 18% burn cover, while the forest-tundra supports 2% burn cover (Table 4). The discrepancy in burn cover between the forest-tundra regions of northwestern Canada and northern Quebec might arise from a) differences in fire regime or regeneration times or b) differences in methodology. If we include only that portion of the forest-tundra that lies south of the 1:1 tree:upland tundra isoline, burn cover would approximate 4-10% in northwestern Canada.

Annual Burn Rates and Fire Return Intervals

Fires in the Northwest Territories have been mapped annually from the 1950s to the present in the region lying between 60°N and the tree line, covering a total area of 1 227 000 km^2 (R.P. Bailey and R.A. Lanoville, pers. comm. 1990). While the area of fire-suppression activities has fluctuated over time due to changes in government policy, the total area over which fires have been mapped has remained relatively constant. This mapping, however, has been carried out with more consistency and greater effort in recent years (Bailey and Lanoville, pers. comm. 1990). For the period 1980-90, the fire action zone (FAZ) measured 252 000 km^2 and the observation zone (OBZ) 975 000 km^2; in comparison, the FAZ for the period 1967-74 measured 338 000 km^2 and the OBZ some 889 000 km^2 (Bailey and Lanoville, pers. comm. 1990).

Annual burn rates and fire return intervals show a trend of increasing fire activity from the 1950s through the 1970s

(Table 7). Fire activity in the 1980s decreased slightly relative to the 1970s but remained well above levels observed between 1950 and 1969. Such trends may be more apparent than real, as missing data are suspected from the early years of fire mapping (Bailey and Lanoville, pers. comm. 1990). The higher burn rates of recent decades, if real, suggest a more severe fire climate in northwestern Canada (Stocks, 1983) and might be linked to global warming.

TABLE 7. Total area burned, annual burn rate, and fire return interval for the Northwest Territories south of the tree line for various periods 1950-89*#

Period	n(yrs)	Total area burned (%)	Annual burn (%)^	Fire return interval (yrs)
1950-59	10	1.394	.139 ± .129	717
1960-69	10	1.487	.149 ± .154	673
1970-79	10	4.623	.462 ± .544	216
1980-89	10	4.158	.416 ± .371	241
1950-69	20	2.881	.144 ± .142	695
1950-79	30	7.504	.250 ± .371	400
1950-89	40	11.662	.292 ± .371	343

* Fire data for the period 1950-79 from Murphy *et al.* (1981); data for the period 1980-89 from National Research Council of Canada (1990).
# Total area burned and annual burn corrected to percentage of landscape by adjusting for an average cover of water bodies of 15%.
^ ± 1 standard deviation.

For the 30-year period most relevant to the air photos used in this study (1950-79), the total area burned in the Northwest Territories was 7.50% of the land surface, giving an annual burn rate of 0.25% ± 0.37 S.D., and a fire return interval of 400 years (Table 7).

An independently derived annual burn rate and fire return interval may be estimated from the mean percentage cover of burn (Table 4) related to regeneration times. We assume regeneration times of 25 years for the closed crown, 37.5 years for the open crown, and 50 years for the forest-tundra regions. The estimated annual burn rate and fire return interval are: for the closed crown forest 0.596% and 168 years; for the open crown forest 0.467% and 214 years; and for the forest-tundra 0.034% and 2941 years.

By comparison with northern Quebec, Payette *et al.* (1989) present data for the period 1950-79 that yield an annual burn rate and fire return interval of 0.532% and 188 years for the open crown forest and 0.518% and 193 years for the forest-tundra. These data suggest that the fire regime of the open crown forest region for the period 1950-79 was similar across northern Canada, while the fire regime of the forest-tundra of northern Quebec was more severe than that of northwestern Canada.

For the period 1970-79, however, annual burn rates and fire return intervals for the Northwest Territories south of the tree line reached all-time recorded highs at 0.462% and 216 years (Table 7); those for northern Quebec were comparatively much lower, at 0.095% and 1519 years for the forest-tundra and 0.010% and 10 417 years for the open crown region (after Payette *et al.*, 1989:Table 2).

Due to wide annual and decadal variability in fire patterns, comparison of fire regimes among widely separated geographic regions requires use of identical time periods. By the same token, a fire regime for a given area might apply strictly to the time period of the data.

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