Proc. 2nd Int. Conf. FOREST FIRE RESEARCH
Vol. II, C.09, pp.625-636, Coimbra, Nov. 1994.

FIRE REGIME AND THE ABUNDANCE OF JACK PINE

M.D. Flannigan and B.M. Wotton

Canadian Forest Service, Petawawa National Forestry Institute.
P.O. Box 2000, Chalk River, Ontario K0J 1J0 Canada.

SUMMARY

Jack pine (Pinus banksiana Lamb.) is common in the boreal forests of North America. Many boreal forest tree species are dependent on semi-regular occurrence of large stand replacing forest fires and jack pine is no exception. This study examines the relationship between the fire regime and the abundance of jack pine as derived from forest inventory data. Given that the autecology of jack pine is closely tied to the fire regime, it is hypothesized that the fire regime is strongly linked to the abundance of this species. The fire regime is represented by components of the Canadian Fire Weather Index System and by headfire intensities calculated from the Canadian Forest Behavior Prediction System.

Results from a linear regression explained 40% of the variance in jack pine volume (abundance) data. Important explanatory variables selected in the regression analysis included the extreme fine fuel moisture code, the annual maximum headfire intensity and the average build up index which is a measure of total available fuel. These results suggest that jack pine abundance is related to the fire regime.

INTRODUCTION

Jack pine (Pinus banksiana Lamb.) is the most widely distributed pine species in Canada. The range of jack pine extends from the Mackenzie Valley in the Northwest Territories southeastward in a broad swath to the upper Great Lakes and thence eastward to the Atlantic Ocean (Figure 1) (Burns and Honkala 1990). This distribution corresponds approximately to the Boreal Forest Region (Rowe 1972). In western Canada, the range of jack pine overlaps with lodgepole pine (Pinus contorta Dougl.) where some hybridization between these two similar species takes place (Wheeler and Guries 1987). Jack pine survived the most recent glaciation in refugia in the Appalachians and at two or more sites in the Midwest United States (Critchfield 1985).

The fire regime[1] is intimately linked to the autecology of jack pine. Most jack pine stands originated after a stand-replacing fire, usually an high intensity crown fire typical

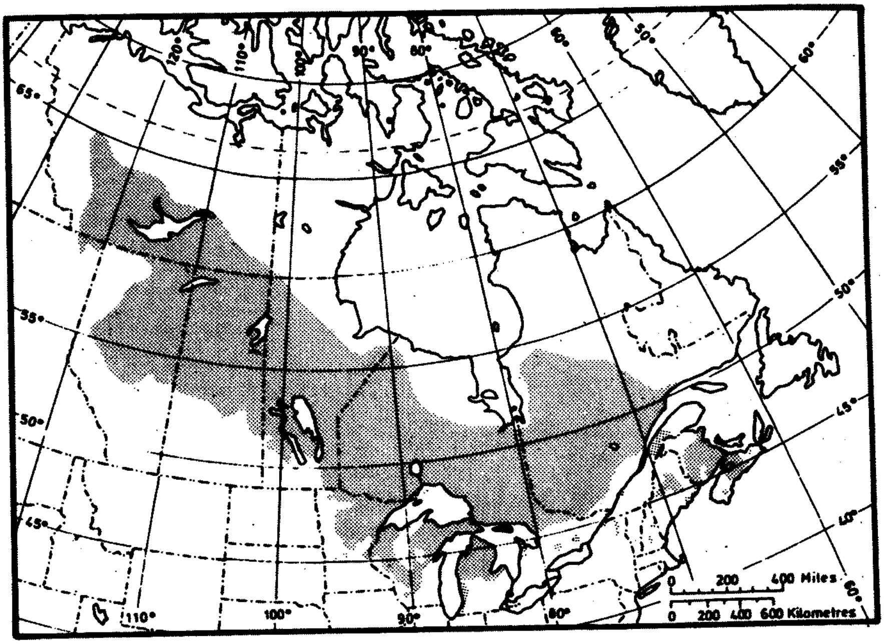

Figure 1.Native Range of jack pine.

of the boreal forest. Of particular interest is the serotiny of most jack pine cones. Temperatures of 50°C or higher are required to melt the resin and allow the cones to open (Mutch 1970). During a forest fire, if the temperatures in the crown are high enough, the resin melts and the seeds disperse. These serotinous cones allow jack pine to regenerate in a stand even if all jack pine trees are killed by the fire. Trees with non-serotinous cones are found in the southern sections of the species' range and in juvenile trees (Gauthier et al. 1993). Thus, jack pine has adapted to and is dependent upon the periodic occurrence of fire. Fire is also important for certain other requirements of jack pine regeneration. The species is intolerant of shade and requires mineral soil for germination and establishment. Fire fulfils these requirements by opening the canopy, removing the organic layer and eliminating competition. Therefore, jack pine thrives in environments with semi-regular lethal fires (Desponts and Payette 1992). However, if

[1] The fire regime has four components: fire intensity, fire frequency, timing(season) of the fire and fire size (Malanson 1987).

lethal fires are too infrequent jack pine may be replaced by more shade tolerant species except on xeric sites(Bergeron and Dubuc 1989). Conversely, if lethal fires are too frequent jack pine will not have a chance to regenerate.

The objective of this study was to examine and to quantify the relationship between the fire regime variables and the abundance of jack pine. Since the autecology of jack pine is so strongly connected to the fire regime (Heinselman 1973) it is hypothesized that the fire regime is closely linked to the abundance of jack pine. The abundance of jack pine should be related to fire intensity and fire frequency as discussed above. Flannigan (1993) found that extreme headfire intensity by itself explained nearly 50% of the variance in red pine (Pinus resinosa Ait.) abundance which, like jack pine abundance, is dependent on fire.

DATA AND METHODS

Forest inventory data and climate data were used in this study. Forest inventory data were obtained from the Canadian Forest Service using the 1991 inventory. Jack pine volume per unit area ($m^3 \cdot ha^{-1}$) were obtained for 45 forest sections in Canada as described by Rowe (1972) (Figure 2). These forest sections were derived from eight forest regions subdivided into forest sections on the basis of distribution patterns of vegetation and physiography. In this study, the abundance of jack pine is represented by volume per hectare. Climatic data were obtained from the Environment Canada's Atmospheric Environment Service. Forty-nine climate stations were used in this study (Figure 3). The data included air temperature and relative humidity recorded inside a Stevenson screen at 1.5m above ground, wind speed measured at 10m above ground and the 24h precipitation. All observations were at 1200 LST for the period April 1 to September 30 which bounds the fire season in jack pine forests. This climate data is for the period of 1953-1991 for the majority of the 49 stations.

Climatic variables were used to calculate components of the Canadian Fire Weather Index (FWI) System (Van Wagner 1987). The Canadian FWI System comprises three fuel moisture codes and three fire behavior indexes. The three moisture codes represent the moisture content of the fine fuels (Fine Fuel Moisture Code (FFMC)), loosely compacted organic matter (Duff Moisture Code), and the deep layer of compact organic

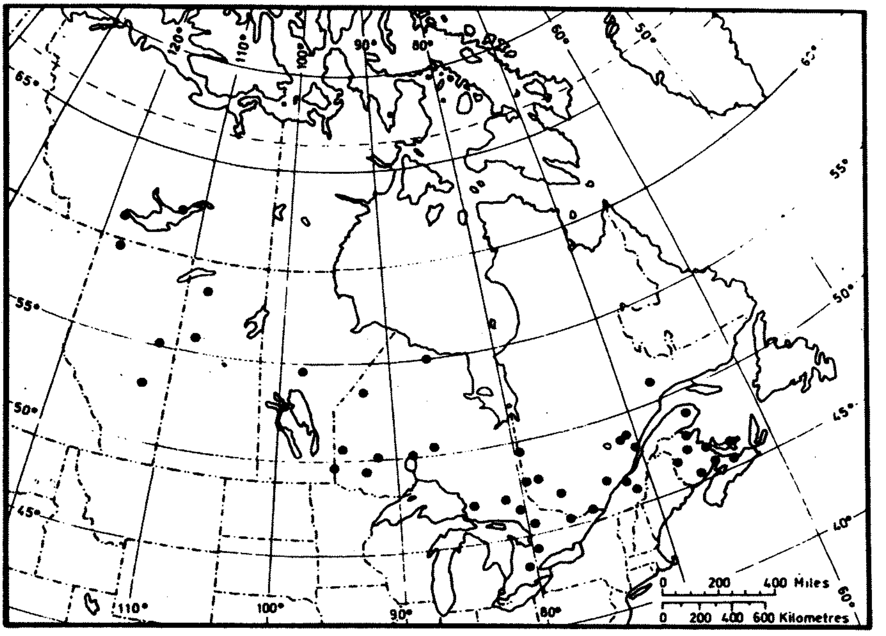

Figure 2. Centroid location of forest inventory data.

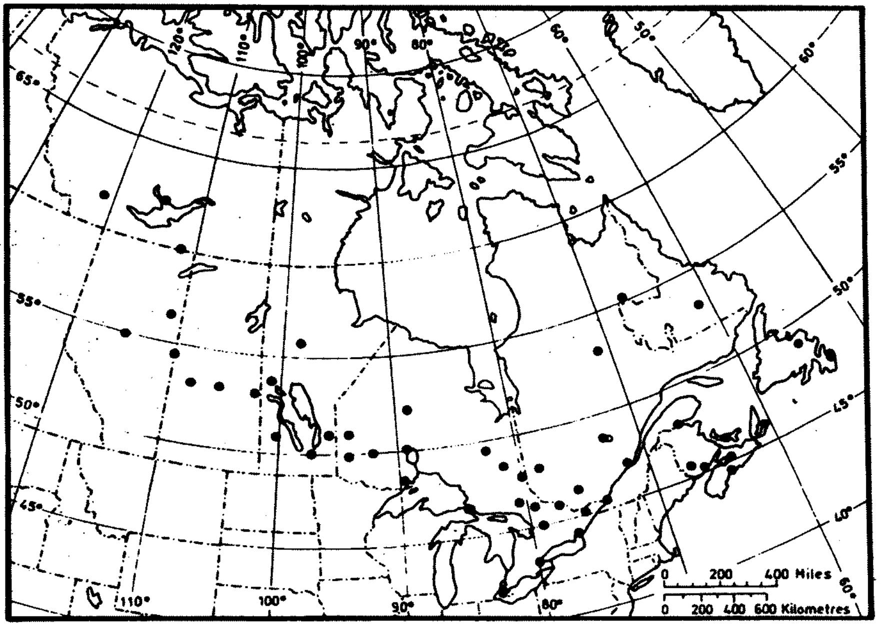

Figure 3. Location of climate stations.

matter (Drought Code). The three fire behavior indexes, which are derived from the moisture codes and the surface wind, indicate the rate of initial fire spread (Initial Spread Index), total available fuel (Build Up Index (BUI)), and the intensity of spreading fire (Fire Weather Index). The Canadian Fire Behavior Prediction (FBP) System (Forestry Canada 1992) was also employed to quantify the potential intensity of forest fires given the necessary meteorological information. The FBP System provides quantitative estimates of headfire spread rate, fuel consumption, fire intensity and fire description (crown fraction burned) for 16 different fuel types. The headfire intensity[2] ($kW{\cdot}m^{-1}$) was calculated for three standard fuel types in the FBP System (C3 (mature jack pine), C4 (immature jack pine), M2 (mixedwood green)). These fuel types were selected because they represent the range of fuel complexes in which jack pine is found in natural settings. The headfire intensity was calculated using the average annual maximum and the extreme maximum of the FFMC, BUI and wind speed.

The climate and inventory data were combined by interpolating the abundance data from 45 inventory sites to the 49 climate stations using a thin-plate cubic spline (Duchon 1976, Thiebaux and Pedder 1987). This method of combination was selected because some of the climate data are dependent on the local site whereas the inventory data are representative of a large area. A thin-plate cubic spline fits a surface to the existing data, in this case latitude, longitude and jack pine volume. The volume of jack pine was estimated at the 49 climate stations from this cubic spline surface.

Independent variables selected to explain variations in abundance included the average, average annual maximum and extreme maximum for the six components of the FWI System and the average annual maximum and extreme maximum headfire intensity for the three standard fuel types in the FBP system (C3, C4 and M2). Extremes were used in this study because only a few days with extreme fire weather conditions are responsible for most of the area burned (Flannigan and Harrington 1988). Additionally,

---

[2] Fireline intensity was originally defined by Byram (1959) as:

$$I=HwR$$

where I is the intensity of the fire ($kW{\cdot}m^{-1}$); H is the low heat of combustion for the fuel ($kJ{\cdot}kg^{-1}$) a standard value of 18 000 $kJ{\cdot}kg^{-1}$ is given for H; w is the weight of the fuel consumed per unit area in the active fire front ($kg{\cdot}m^{-1}$); and R is the rate of forward spread ($m{\cdot}s^{-1}$).

a study relating components of the FWI System to monthly provincial area burned by wildfire revealed that extreme values of the components explained the most variance, particularly when looking at regions the size of provinces (Harrington et al. 1983).

A forward-stepwise regression (SAS Institute Inc. 1990) was used to investigate the partitioning of the variance in the jack pine volume data in terms of the fire regime as represented by the components of the FWI System and FBP System. Terms were accepted only if they met the 0.05 significance level, which corresponds to a minimum F-value for entrance of 4.0; terms were removed if they failed to meet the 0.05 significance level.

RESULTS

Equation 1 is the result of the forward-stepwise regression performed on our data.

$$Vol^{a} = -241.32 + 2.519\cdot(\text{extreme FFMC}) + 0.155\cdot(\text{annual max. headfire intensity fuel M2}) + 0.157\cdot(\text{mean BUI}) \quad (1)$$

Variance =	32%	4%	4%
Explained	40%		

[a]Vol is an abbreviation for the volume of jack pine ($m^3 \cdot ha^{-1}$)

In equation 1 the extreme FFMC was selected first and, as a single variable, it explained the most variance (32%). The second and third variables added to the regression were, respectively, the annual maximum headfire intensity for fuel type M2 and the average BUI. Figure 4 illustrates that the extreme FFMC is positively correlated with the abundance of jack pine, i.e., the higher the FFMC the greater the volume of jack pine. Additionally, the headfire intensity for fuel type M2 and the average BUI also show positive correlations with the volume of jack pine (Table 1). In fact, all the variables used in this study show positive correlations with the volume of jack pine.

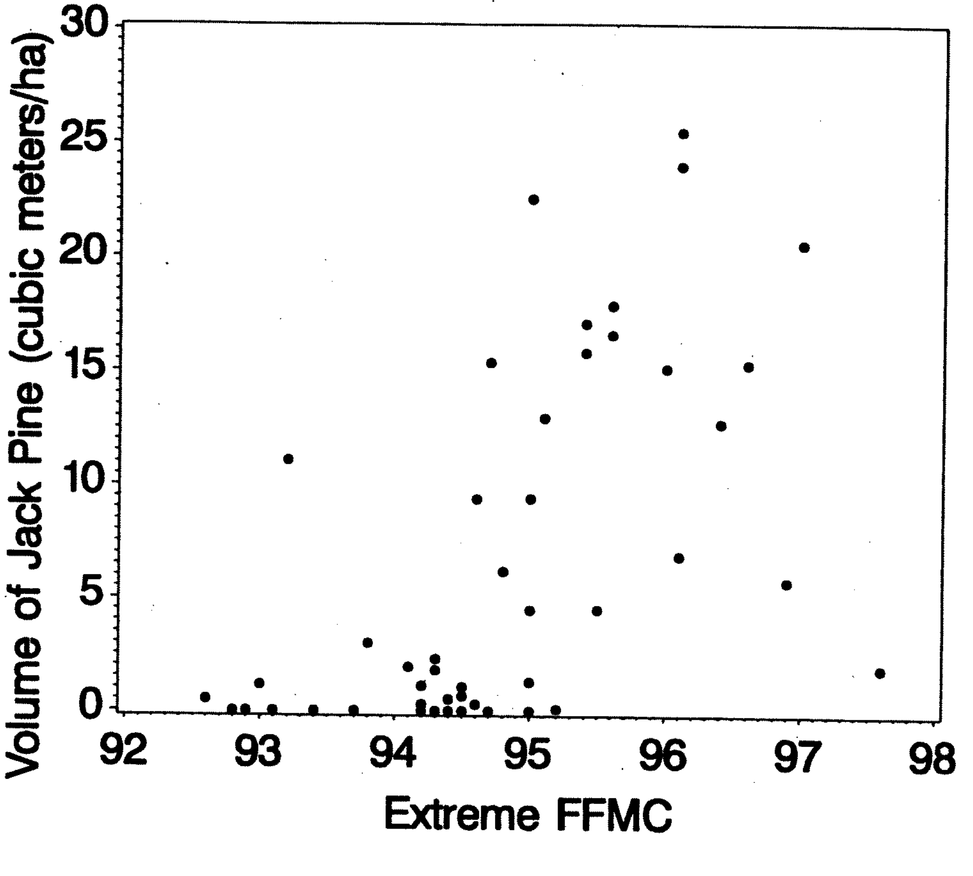

Figure 4. Volume of jack pine ($m^3 \cdot ha^{-1}$) versus extreme FFMC.

Table 1. Correlation coefficients and variance explained for jack pine volume by individual variables.

Variable	Correlation	Variance Explained (%)
Fine fuel moisture code	0.41	17
Fine fuel moisture code*	0.56	31
Fine fuel moisture code**	0.56	32
Duff moisture code	0.40	16
Duff moisture code*	0.41	17
Duff moisture code**	0.37	14
Drought code	0.35	12
Drought code*	0.28	8
Drought code**	0.37	14
Initial spread index	0.38	15
Initial spread index*	0.32	10
Initial spread index**	0.37	14
Build up index	0.42	18
Build up index*	0.35	12
Build up index**	0.37	14
Fire weather index	0.42	17
Fire weather index*	0.44	19
Fire weather index**	0.47	22
Headfire intensity C3*	0.40	16
Headfire intensity C3**	0.44	19
Headfire intensity C4*	0.40	16
Headfire intensity C4**	0.45	21
Headfire intensity M2*	0.41	17
Headfire intensity M2**	0.34	12

* Average annual maximum
** Extreme maximum recorded
A variable with no '*' indicates an average value.

DISCUSSION

It is interesting that the extreme FFMC explains the most variance in the volume of jack pine data. The FFMC is used to derive the initial spread index which, in turn, is used to calculate the rate of spread for a fire (R) which then is used in Byram's equation (I=HwR) to calculate headfire intensity. Thus, the FFMC is linked to headfire intensity; a relationship between fire intensity and jack pine abundance was, therefore, expected.

However, the headfire intensity for three fuel types was calculated directly, which prompts the question... 'Why does the extreme FFMC explain more variance than the headfire intensities?' One possible explanation is that the FFMC is related to the probability of occurrence of fire. The higher the FFMC the more a likely fire will occur if subjected to an ignition agent. Martell et al. (1987) found that the FFMC was the most important variable in predicting people-caused fire occurrence in northern Ontario. The actual range of the extreme FFMC at the 49 stations ranged from 92.6 to 97.6. Although the numerical range of the extreme FFMC in this study is small, the difference in fire behavior is large. For example, given a moderate fuel load, the rate of spread and headfire intensity of a fire with a FFMC of 96.7 is almost twice as large as the rate of spread and headfire intensity of a fire with a FFMC of 92.6. The results support the hypothesis that jack pine volume is related to fire intensity. For each fuel type the headfire intensity explained approximately the same amount of variance (12-21% Table 1) and was always positively correlated with abundance. Weber (1988) found that fire intensities of 17 000 $kW \cdot m^{-1}$ are required for adequate regeneration and that the best growth was achieved at sites exposed to the highest fire intensity. Landscapes where fires are more intense (for example, lethal crown fire) are where the most jack pine is found. This is in contrast to the inverse relationship (negative correlation) between red pine abundance and headfire intensity (i.e., the higher the headfire intensity the less abundant is red pine (Flannigan 1993)). Another aspect of fire intensity is the role it plays in opening the cones by exposure to high temperature (Beaufait 1954). Johnson and Gutsell (1993) have developed a relationship between rate of fire spread and fire intensity to determine cone opening and ignition. Unfortunately, no measure of fire frequency was used in this study which might help us to better understand the relationship between fire regime and jack pine volume.

The average BUI was the third and final variable selected in the regression equation. The BUI is used to calculate the intensity of a fire and is a measure of the total fuel available. It is also a measure of the moisture content in the organic layer and in the heavier fuels. A higher BUI will result in more fuel being consumed in a fire. Thus, the index may be an indicator of the importance of seed bed preparation for regeneration of jack pine.

Extreme values appear to be important in the fire regime - jack pine abundance relationship. Fire, especially lethal fire, at any one location is a rare event that happens once every 20-100 years in the natural boreal forest (Stocks and Lynham 1991). Statistics show that a small percentage of fires are responsible for the majority of the area burned (3% of the fires are responsible for 98% of the area burned (Ramsey and Higgins 1992)). These large forest fires tend to occur on a few critical days where the weather and fuels are conducive to intense and large forest fires. Therefore, extreme values of these fire regime variables associated with these critical fire weather days should be related the abundance of jack pine. Further, any studies looking at the impact of a changing climate on the fire regime should consider the frequency of extremes in their analysis.

This study addressed the large scale relationship between fire regime and abundance of jack pine. Soils, site and vegetational history play a major role in determining the presence and abundance of tree species at the local level. These factors have been ignored in the present study and may, in part, be responsible for the unexplained variance in abundance data. However, since each data point represents large regions with a variety of landscapes the influence of these factors might be marginal in our study.

Recent developments are influencing the abundance of jack pine. Some examples include a fire exclusion policy and harvesting the forest for profit and for agricultural development. Most of these developments were initiated during the 20th century for much of the boreal forest and the ramifications from these anthropogenic influences are not completely realized. For example, in Ontario the average annual area burned during the pre-suppression era was over 700 000 ha compared to the present day value of just over 80 000 ha (Ward and Tithecott 1993). The effect of a fire management policy of fire exclusion will have a considerable influence on the abundance of jack pine. Existing jack pine forests may be changing to those having more shade tolerant species like balsam fir (Abies balsamea (L.) Mill.) because of these fire management policies. Our forest inventory data has been influenced by these activities and may be responsible for some of the unexplained variance in the data.

Future research will focus on the relationship between climate and the abundance of jack pine and the combined role of fire regime and climate on jack pine abundance.

REFERENCES

Beaufait, W.R. 1960. Some effects of high temperatures on the cones and seeds of jack pine. For. Sci. 6:194-199.

Bergeron, Y., and Dubuc, M. 1989. Succession in the southern part of the Canadian boreal forest. Vegetatio 70:51-63.

Burns, R.M. and B.H. Honkala. 1990. Silvics of North America trees. 1. Conifers. USDA Forest Service, Washington, D.C. Agriculture Handbook 654.

Byram, G.M. 1959. Forest fire behavior. In Forest fire: Control and use. Edited by Davis, K.P. McGraw-Hill, New York.

Critchfield, W.B. 1985. the late Quaternary history of lodgepole and jack pines. Can. J. For. Res. 15:749-772.

Desponts, M. and Payette, S. 1992. Recent dynamics of jack pine at its northern distribution limit in northern Quebec. Can. J. Bot. 70:1157-1167.

Duchon, J. 1976. Interpolation des fonctions de deux variables suivant le principe de la flexion des plaques minces. Revue français d'automatique, informatique, recherche opérationnelle: Analyse Numérique 10:5-12.

Flannigan, M.D. and J.B. Harrington. 1988. A study of the relation of meteorological variables to monthly provincial area burned by wildfire in Canada 1953-80. J. of Appl. Meteorol. 27:441-452.

Flannigan, M.D. 1993. Fire regime and the abundance of red pine. Intl J. Wild. Fire 3:241-247.

Forestry Canada. 1992. Development and Structure of the Canadian Forest Fire Behavior Prediction System. For. Can. Inf. Rep. ST-X-3, Ottawa.

Gauthier, S., Bergeron, Y. and Simon, J.-P. 1993. Cone serotiny in jack pine: ontogenetic, positional and environmental effects. Can. J. For. Res. 23:394-401.

Harrington, J.B., M.D. Flannigan, and C.E. Van Wagner. 1983. A study of the relation of components of the Fire Weather Index to monthly provincial area burned by wildfire in Canada 1953-80. Environ. Can., Can. For. Ser., Petawawa Natl. For. Inst. Inf. Rep. PI-X-25.

Heinselman, M.L. 1973. Fire in the virgin forests of the Boundary Waters Canoe Area, Minnesota. Quaternary Res. 3:329-382.

Johnson, E.A. and Gutsell, S.L. 1993. Heat budget and fire behaviour associated with the opening of serotinous cones in two Pinus species. J. Veget. Sci. 4:745-750.

Malanson, G.P. 1987. Diversity, stability and resilience: effects of fire regime. In The role of fire in ecological systems. Edited by L. Trabaud. SPB Academic Publishing, The Hague.

Martell, D.L., Otukol,S. and Stocks, B.J. 1987. A logistic model for predicting daily people-caused forest fire occurrence in Ontario. Can. J. For. Res. 17:394-401.

Mutch, R.W. 1970. Wildland fires and ecosystems - a hypothesis. Ecology 51:1046-1051

Rowe, J.S. 1972. Forest regions of Canada. Environ. Can., Ottawa.

Ramsey, G.S. and Higgins, D.G. 1992. Canadian Forest Fire Statistics. For. Can., Petawawa Natl. For. Inst., Inf. Rep. PI-X-107.

SAS INSTITUTE INC. 1990. SAS User's Guide: Statistics, version 6. SAS Institute Inc., Cary, NC.

Stocks, B.J. and Lynham, T.J. 1991. The natural fire regime of an unprotected section of the boreal forest in Canada. Pages 99-109 in Seventeenth Tall Timbers Fire Ecology Conf. May 18-21, 1989. Tallahassee, FL.

Thiebaux, H.J. and M.A. Pedder. 1987. Spatial objective analysis: with applications in atmospheric science. Academic Press, London.

Van Wagner, C.E. 1987. Development and structure of the Canadian Forest Fire Weather Index System. Can. For. Ser., Tech. Rep. 35.

Ward, P.C. and A.G. Tithecott. 1993. The impact of fire management on the boreal landscape of Ontario. Aviation, Flood and Fire Management Branch Publication No. 305.

Weber, M. G. 1988. Fire and ecosystem dynamics in eastern Canadian Pinus banksiana forests. Pages 93-105 in Vegetation structure in relation to carbon and nutrient economy. Edited by Verhoeven , J.T.A. et al. SPB Academic Publishing, The Hague.

Wheeler, N.C. and R.P. Guries. 1987. A quantitative measure of introgression between lodgepole and jack pines. Can. J. Bot. 65:1876-1885.