

Hogg 1994

TEMPORAL SCALING ISSUES AND THE
SOUTHERN BOUNDARY OF THE WESTERN
CANADIAN BOREAL FOREST

Edward H. Hogg

Northern Forestry Centre, Canadian Forest Service

5320-122 Street, Edmonton AB T6H 3S5, Canada

SUMMARY

Recent global change predictions indicate relatively large changes in the future climate of the western Canadian interior. Moisture deficiency could become a critical factor driving future change in the southern boreal forest of western Canada, where the climate is presently much drier than its counterparts in eastern North America and Europe.

Analyses of vegetation-climate relationships have been conducted as a simple temporal scaling technique to identify the most important processes controlling the southern boundary of the boreal forest in western Canada. In a previous study, thermal characteristics of climate, such as growing degree days and summer temperature, were found to correspond poorly with forest zonation in this region. In contrast, a close fit was found between the southern boundary and the isoline where annual precipitation (P) equals potential evapotranspiration (PET), using the empirical Jensen-Haise method. In the present study, a similar result was obtained, when PET was estimated using a highly simplified version of the Penman-Monteith equation. These results indicate that the southern limit of the western Canadian boreal forest is governed, either directly or indirectly, by moisture deficiency.

Questions concerning long-term, regional processes remain to be answered. First, is the present distribution of the boreal forest determined directly by climate, through drought effects on tree regeneration and survival, or is it a result of a high, drought-induced fire frequency on the prairies in the past? Second, how important is the boreal forest in producing the observed climatic moisture gradient?

FILE COPY / RETURN TO:

PUBLICATIONS
NORTHERN FORESTRY CENTRE
5320 - 122 STREET
EDMONTON, ALBERTA
T6H 3S5

INTRODUCTION

The boreal forest occupies nearly 30% of the Canadian landscape, and also extends over large areas of Alaska, Siberia and northern Europe. This forest type occurs in cold climatic regions, and in Canada, is typically dominated by several species of conifers (e.g. Picea glauca, Picea mariana and Pinus banksiana) with only a few hardwood tree species. In eastern Canada, the boreal forest forms its southern boundary with temperate forests, with a high diversity of hardwoods. However, in western Canada, the boreal forest is bounded to the south by prairie grasslands, where coniferous trees are naturally absent, and hardwoods are mainly restricted to small, stunted groves of aspen (Populus tremuloides) in the most favourable sites.

Recent GCM predictions indicate a warmer, and possibly drier global climate in the future, as the levels of atmospheric carbon dioxide and other greenhouse gases continue to increase (e.g. IPCC 1990, 1992). These effects are expected to be greatest in northern continental regions (e.g. Manabe et al. 1992), including most of the world's boreal forest. This could lead to a prairie-like climate over parts of the southern boreal forest in western Canada (Emanuel et al. 1985; Rizzo and Wiken 1992).

Scaling issues are fundamental to understanding both 1) biological responses of the boreal forest to changes in climate and 2) the feedbacks of the forest on atmospheric and climatic processes. BOREAS (Boreal Ecosystem - Atmosphere Study) is a large, ongoing field experiment in western Canada focusing on processes governing the interaction between the boreal forest and the atmosphere, with an emphasis on how these processes may respond under climate change (Sellers et al. 1991). The experiment is interdisciplinary and has a spatially nested design, which should allow both physical and biological processes to be scaled up, from small spatial scales (e.g. individual leaves and trees) to much larger scales (landscape and region).

Because BOREAS field activities will concentrate on one or two growing seasons, the strongest contribution will be to improve understanding of interscale relationships of diurnal and seasonal processes. However, predicting future responses of the boreal forest will also require an improved insight into ecological responses to climate, many of which operate under much longer time scales (decades to centuries). These include, for example, the effects of climate on tree regeneration and growth, forest succession, fire regimes, and the accumulation of carbon in peatlands.

One of the simplest approaches to address the temporal scaling problem is to examine the spatial relationships which have developed over time between climate and natural vegetation zonation (e.g. Holdridge 1947, Tukhanen 1984). A previous analysis (Hogg 1994) showed that the southern boundary of the boreal forest in western Canada corresponds poorly with thermal characteristics of climate, including July mean temperature and the number of growing degree days. In contrast, this boundary

was found to fit very closely with the isoline where mean annual precipitation (P) equals mean annual potential evapotranspiration (PET), by the Jensen-Haise method. This isoline, where $P-PET=0$, is henceforth referred to as the "zero isoline". Such a result suggests that in western Canada, the southern boundary of the boreal forest is governed either directly or indirectly by moisture rather than temperature (Hogg 1994).

The Jensen-Haise method of estimating PET (Bonan 1989, Jensen et al. 1990) is relatively simple to use, requiring only temperature, altitude, and mean monthly global solar radiation. However, it is empirically based on measurements taken over well-watered grasslands and agricultural crops in the western United States. In contrast, the Penman-Monteith equation is theoretically based, and can be parameterized for any vegetation type, including forests (Jones 1983; Jensen et al. 1990). It is also theoretically suited for interscale, spatial comparisons (e.g. McNaughton and Jarvis 1991) and forms the basis for estimating evapotranspiration in forest ecosystem process models (e.g. Running and Coughlan 1988). Unfortunately, the Penman-Monteith equation normally uses detailed input data (e.g. net radiation, vapour pressure) that are not generally available from the long-term climate record, particularly in remote regions of the boreal forest. The equation also needs vegetation-specific estimates of canopy conductance (both physiological and aerodynamic).

The present analysis uses a simplified form of the Penman-Monteith equation, parameterized for a generic forest, to allow long-term PET estimates from monthly mean daily maximum and minimum temperatures at climate stations in western Canada. The objective was to compare the simplified Penman-Monteith equation and the Jensen-Haise method in terms of the correspondence between the zero isoline (of $P-PET$) and the southern boundary of the boreal forest.

METHODS

Evapotranspiration in forests is more sensitive to vapour pressure deficit than to net radiation because of high aerodynamic conductances (g_a , Jones 1983). Using $g_a = 200 \text{ mm s}^{-1}$, applicable to coniferous forests (Running and Coughlan 1988), the net radiation term of the Penman-Monteith equation was found to contribute only $5.0 \pm 0.4\%$ of total PET for the three stations in the region (Bad Lake, Saskatchewan; Churchill, Manitoba and Edmonton, Alberta) where long-term net radiation data are available (Environment Canada 1982a). Thus for this application, the Penman-Monteith equation (Jensen et al. 1990) could be simplified to the following, which requires only the mean maximum and minimum temperature for each month:

$$PET = \frac{1.05 k \rho c_p D g_a}{\lambda (\Delta + \gamma (1 + g_a/g_c))} \quad [1]$$

where:

D = mean vapour pressure deficit (kPa), estimated as:

$(e_{\max} - e_{\min})/2 - e_{\text{dew}}$ (Jensen et al. 1990); e_{\max} and e_{\min} are the saturation vapor pressures for the mean maximum and minimum daily temperatures for each month; e_{dew} is the saturation vapor pressure at dewpoint temperature. As a first approximation in this preliminary analysis, the dewpoint was assumed to be 2.5°C less than mean minimum temperature, which corresponds to the mean nightly maximum relative humidity (May-September) of 84% at Saskatoon.

k = proportionality constant, seconds per month;

ρ = mean density of air (kg m^{-3}) at mean station pressure and mean monthly temperature (T_{mean});

c_p = heat capacity of air ($1.012 \text{ kJ kg}^{-1} \text{ }^\circ\text{C}^{-1}$);

Δ = slope of saturation vapour pressure ($\text{kPa } ^\circ\text{C}^{-1}$) at T_{mean} ;

λ = latent heat of vaporization (MJ kg^{-1}) at T_{mean} ;

γ = psychometric constant at mean station pressure ($\text{kPa } ^\circ\text{C}^{-1}$);

g_a = aerodynamic conductance of forests (200 mm s^{-1} assumed);

g_c = average canopy conductance (mm s^{-1})

Canopy conductance (g_c) is highly variable, being controlled largely by stomatal responses to environmental conditions, but typically ranges from 1-10 mm s^{-1} in both forests (coniferous and deciduous) and native grasslands (Jones 1983). However, the apparent sensitivity of transpiration to changes in g_c decreases as the spatial scale under investigation increases; McNaughton and Jarvis (1991) and their earlier analyses provide a more comprehensive theoretical framework for spatial scaling of the processes governing transpiration.

In the present, highly simplified analysis, a standard mean canopy conductance g_{cs} of 5 mm s^{-1} was used for mean monthly temperatures $>10^\circ\text{C}$, but other values of g_{cs} were also tested. In all analyses, a linear reduction in g_{cs} to 0 mm s^{-1} was assumed to occur as mean monthly temperature decreases from 10°C to -5°C . This is meant to reflect the effects of cold or frozen soils, subfreezing night temperatures and dormancy on evaporation and conductance (Running and Coughlan 1988). Because g_{cs} is

expressed in standard units (mm s^{-1}), it is affected by the purely physical effects of temperature and pressure (altitude) at a given degree of stomatal opening. Corrected conductance (g_c) was thus calculated from conductance in standard units (g_{cs}) according to Jones (1983).

Mean monthly PET was calculated for each of the twelve months using Equation [1], using the 1951-1980 long-term climate normals (Environment Canada 1982b) from 254 stations in the region. Mean annual PET was then determined as the sum of the monthly values. Finally, a climate moisture index was calculated for each station as P-PET (annual precipitation minus PET, with units in cm).

RESULTS AND DISCUSSION

The analysis showed a close correspondence between the southern boundary of the boreal forest in western Canada and the zero isoline of the P-PET climate moisture index, based on the simplified Penman-Monteith equation with $g_{cs} = 5 \text{ mm s}^{-1}$ (Figure 1). The position of this isoline is very similar to that obtained in a previous study using the Jensen-Haise method (Hogg 1994, also shown in Figure 1) and the Priestley and Taylor (1972) method (Hogg, unpublished). These results indicate that in the western Canadian interior, the boreal forest is restricted to areas where there is a surplus of precipitation over potential evapotranspiration. The boundary between the foothills forest and prairie near Calgary also corresponds to the zero isoline where $P=PET$ (Figure 1).

It should be noted that the estimates of PET using the simplified Penman-Monteith equation are highly sensitive to the value of canopy conductance (g_{cs}) used. At Edmonton, Flin Flon and Winnipeg (Figure 1), PET was found to increase nearly in direct proportion to values of g_{cs} between 4 and 6 mm s^{-1} (Table 1). The PET estimates in this analysis are also affected by the method of estimating vapour pressure deficit. Thus the position of the zero isoline using this equation is strongly dependent on the parameterization. In contrast, the PET estimates based on the more empirical Jensen-Haise equation are uniquely determined by a station's elevation, global solar radiation and temperature.

In western Canada, the zero isoline where $P=PET$ corresponds to a sharp discontinuity in several landscape characteristics and processes. Hydrologically, the isoline corresponds to a sharp regional gradient in the quantity of annual runoff, ranging from <2.5 cm per year in the grassland to the south to > 10 cm per year over most of the boreal forest (Fisheries and Environment Canada 1978). South of this isoline where chronic moisture deficits occur ($P<PET$), conifers and peatlands are generally absent (Zoltai 1975, Vitt et al. 1994, Hogg 1994), aspen is restricted to small patches and has a stunted growth form, and lakes tend to dry up during periods of drought (Campbell et al.

1994). The intensity, severity and extent of forest fires is also strongly affected by weather conditions, particularly moisture. The drought of 1988-89, for example, caused fires to burn over three million hectares of boreal forests and peatlands in northern Manitoba (Hirsch 1991). Unusually poor regeneration of jack pine (Pinus banksiana) has been noted, following one of the large 1989 fires in Saskatchewan. This drought also led to massive dieback of aspen in the northern grassland region (pers. obs).

These effects might increase in the future, if increasing atmospheric CO₂ levels lead to a warmer and drier climate. This could also lead to major feedbacks on atmospheric CO₂ levels (c.f. Tans et al. 1990) and in the energy balance of the regional landscape (e.g. Bonan et al. 1992). Feedbacks of this type include immediate impacts, such as those produced by large-scale fire or drought, and longer-term responses, including chronic reductions in forest regeneration and growth, increased decomposition of forest soils and peatlands, and melting of permafrost. Such processes cannot be adequately assessed solely through intensive, short-term ecophysiological, hydrologic and meteorological studies.

Historical analyses of past ecosystem responses to climate, coupled with simulation modelling of long-term processes, can be a powerful approach to understand these longer term processes. This approach forms part of the Climate Change Initiative of the Canadian Forest Service. Current studies are relying on dendrochronology, palynology and peat stratigraphy, surveys of decomposition rates, tree growth and biomass, and seedling regeneration across regional climate gradients. Modelling initiatives include a carbon budget model (Kurz and Apps 1994), and forest growth models patterned after FORSKA (Prentice et al. 1993) and FOREST-BGC (Running and Coughlan 1988).

One of the problems in assessing drought effects, even on a 50-100 year time scale, is the scarcity of detailed weather data. Such data is available for our region, but early data are mainly limited to observations of temperature and precipitation. However, the simplified Penman-Monteith approach presented here can use this limited information to estimate PET on a daily, monthly, or annual time-step. Temporal changes in the climate moisture index (P-PET) can then be estimated and applied, for example, to studies of tree-ring responses to climatic moisture deficits (Hogg, unpublished).

Other questions concerning long-term, regional processes remain to be answered. For example, is the southern boundary of the western Canadian boreal forest determined directly by climate, through drought effects on tree regeneration and survival, or is it a result of a high, drought-induced fire frequency on the prairies in the past? If the present forest distribution is strictly climate-limited, then even slight future changes in climate could have a major impact (Hogg 1994). Feedbacks of the vegetation on regional climate may also be important, e.g. to what extent does the presence of boreal forest

produce the observed climatic moisture gradient? These types of questions can only be addressed through continued, interscale and interdisciplinary research efforts, with a much greater emphasis the temporal scaling issue.

ACKNOWLEDGEMENTS (**to be added)

LITERATURE CITED

- Bonan, G.B. 1989. A computer model of the solar radiation, soil moisture, and soil thermal regimes in boreal forests. *Ecol. Modell.* 45: 275-306.
- Bonan, G.B., Pollard, D., and Thompson, S.L. 1992. Effects of boreal forest vegetation on global climate. *Nature* 359:716-718.
- Campbell, C., Campbell, I.D., and Hogg, E.H. 1994. Lake area variability across a climatic and vegetational transect in southeastern Alberta. *Geogr. phys. Quatern.* 48 (in press).
- Emanuel, W.R., Shugart, H.H., and Stevenson, M.P. 1985. Climatic change and the broad-scale distribution of terrestrial ecosystem complexes. *Clim. Change* 7: 29-43.
- Environment Canada. 1982a. Canadian climatic normals 1951-1980. Vol. 1. Solar radiation. Atmospheric Environment Service. Downsview, Ontario, Canada. 57 pp.
- Environment Canada. 1982b. Canadian climatic normals 1951-1980. Temperature and precipitation. Prairie Provinces. Atmospheric Environment Service. Downsview, Ontario, Canada. 429 pp.
- Fisheries and Environment Canada. 1978. Hydrological atlas of Canada. Surveys and Mapping Branch, Dep. Energy, Mines and Resources. Ottawa, Canada. *** pp.
- Hirsch, K.G. 1991. A chronological overview of the 1989 fire season in Manitoba. *For. Chron.* 67: 358-365.
- Holdridge, L.R. 1947. Determination of world plant formations from simple climatic data. *Science* 105: 367-368.
- Hogg, E.H. 1994. Climate and the southern limit of the western Canadian boreal forest. *Can. J. For. Res.* (in press).

- IPCC. 1990. In Climate change. The IPCC scientific assessment. Edited by J.T. Houghton, G.J. Jenkins, and J.J. Ephraums. Cambridge University Press, Cambridge, UK. *** pp.
- IPCC. 1992. In Climate change 1992. The supplementary report to the IPCC scientific assessment. Edited by J.T. Houghton, B.A. Callander, and S.K. Varney. Cambridge University Press, Cambridge, UK. *** pp.
- Jensen, M.E., Burman, R.D., and Allen, R.G. (Editors). 1990. Evapotranspiration and irrigation water requirements. Manuals and Reports on Engineering Practice No. 70. Am. Soc. Civ. Eng., New York.
- Jones, H.G. 1983. Plants and microclimate, a quantitative approach to environmental plant physiology. Cambridge University Press, Cambridge, UK. 323 pp.
- Kurz, W.A., and Apps, M.J. 1994. The Carbon Budget of Canadian forests: a sensitivity analysis of changes in disturbance regimes, growth rates and decomposition rates. Environ. Pollution 83: 55-61.
- Manabe, S., Spelman, M.J., and Stouffer, R.J. 1992. Transient responses of a coupled ocean-atmosphere model to gradual changes of atmospheric CO₂. Part II. Seasonal response. J. Climate 5: 105-126.
- McNaughton, K.G. and Jarvis, P.G. 1991. Effects of spatial scale on stomatal control of transpiration. Agric. For. Meteorol. 54: 279-301.
- Prentice, I.C., Sykes, M.T., and Cramer, W. 1993. A simulation model for the transient effects of climate change on forest landscapes. Ecol. Modell. 65: 51-70.
- Priestley, C.H.B., and Taylor, R.J. 1972. On the assessment of surface heat flux and evaporation using large-scale parameters. Mon. Weather Rev. 100: 81-92.
- Rizzo, B., and Wiken, E. 1992. Assessing the sensitivity of Canada's ecosystems to climatic change. Clim. Change 21: 37-55.
- Running, S.W., and Coughlan, J.C. 1988. A general model of forest ecosystem processes for regional applications I. Hydrologic balance, canopy gas exchange and primary production processes. Ecological Modelling 42: 125-154.
- Sellers, P.J., Cihlar, J., Apps, M., Goodison, B., Hall, F.G., Harriss, R.C., Leckie, D.L., Ledrew, E., Matson, P.A., and Running, S. 1991. BOREAS: global change and biosphere-

atmosphere interactions in the boreal forest biome, Science Plan, NASA Goddard Space Flight Center, Greenbelt, MD. 67 pp.

Tans, P.P., Fung, I.Y., and Takahashi, T. 1990. Observational constraints on the global atmospheric CO₂ budget. Science 247: 1431-1438.

Tukhanen, S. 1984. A circumboreal system of climatic-phytogeographical regions. Acta Bot. Fenn. 127: 1-50.

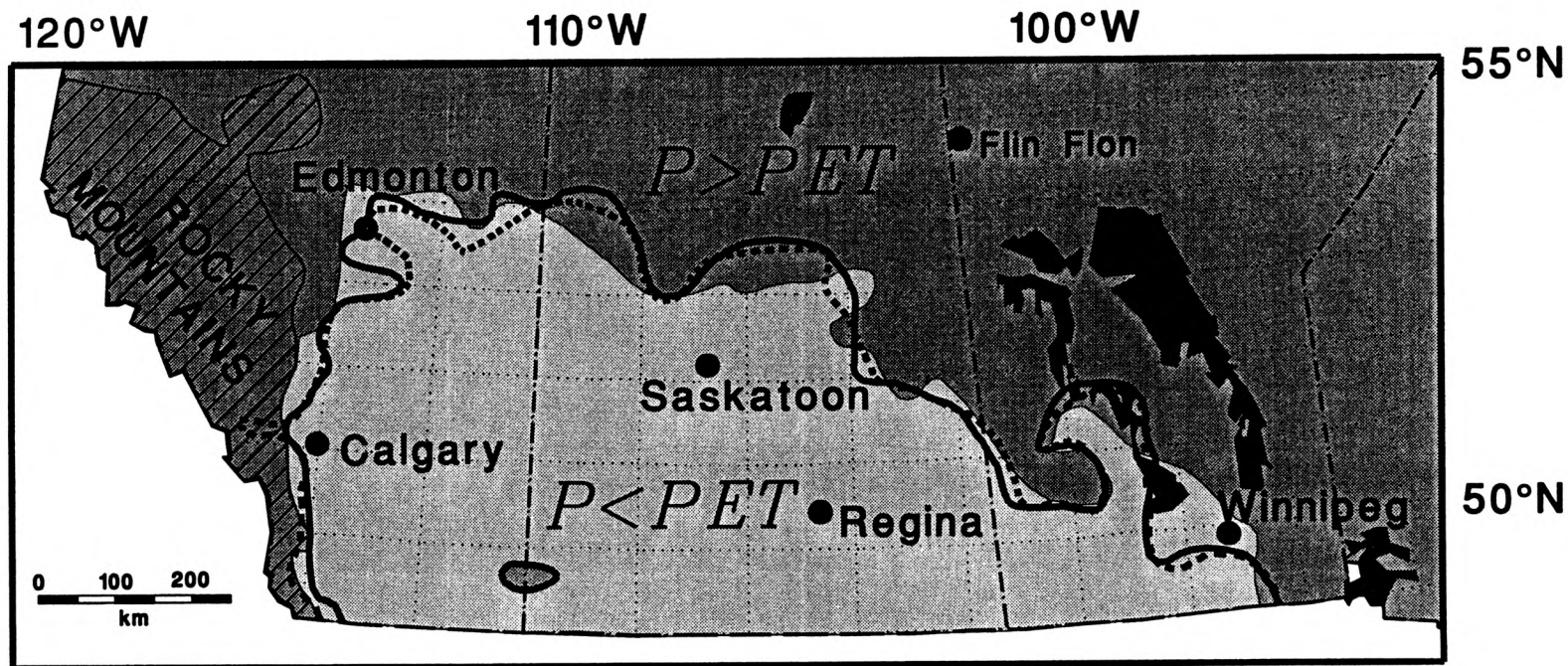
Vitt, D.H., Halsey, L.A., and Zoltai, S.C. 1994. The bog landforms of continental western Canada in relation to climate and permafrost patterns. Arctic and Alpine Res. 26: 1-13.

Zoltai, S.C. 1975. Southern limit of coniferous trees on the Canadian prairies. Information Report NOR-X-128, Canadian Forestry Service, Northern Forest Research Centre, Edmonton, Alberta.

Table 1. Estimates of annual potential evapotranspiration (PET) and climate moisture index (P-PET) using the Jensen-Haise method, and the simplified Penman-Monteith equation under differing values of standard canopy conductance (g_{cs}). Station locations are shown in Figure 1.

	Saskatoon	Flin Flon	Winnipeg
P (Annual Precipitation, mm)	349	446	526
PET (mm) :			
Jensen-Haise method	518	363	499
Penman-Monteith ($g_c = 4$ mm/s)	413	300	404
Penman-Monteith ($g_c = 5$ mm/s)	509	370	499
Penman-Monteith ($g_c = 6$ mm/s)	604	439	592
P-PET, in cm:			
Jensen-Haise method	-16.9	11.3	2.5
Penman-Monteith ($g_c = 4$ mm/s)	-6.4	17.6	12.1
Penman-Monteith ($g_c = 5$ mm/s)	-16.1	10.6	2.7
Penman-Monteith ($g_c = 6$ mm/s)	-25.5	3.7	-6.6

Figure 1. Correspondence of the southern limit of forest distribution in the interior of western Canada with the zero isolines of P-PET using the simplified Penman-Monteith equation ($g_c = 5 \text{ mm s}^{-1}$) and the Jensen-Haise method. Political boundaries of three provinces are shown (Alberta, Saskatchewan and Manitoba, from left to right). Forest outlier near 50°N , 110°W belongs to the Cypress Hills (P-PET = +5 cm by Penman-Moneith method).



FOOTHILLS FOREST



BOREAL FOREST



LAKES



GRASSLAND

ZERO P-PET ISOLINES:



PENMAN-MONTEITH



JENSEN-HAISE



Memorial

University of Newfoundland

CONTINUING ENGINEERING EDUCATION

in conjunction with



THE INTERNATIONAL UNION OF FORESTRY RESEARCH ORGANIZATIONS

SG 1.03.02: Global Perspectives on
Environmental Influences on Forests, SG 201: Physiology

and in co-operation with

DEPARTMENT OF NATURAL RESOURCES CANADA
CANADIAN FOREST SERVICE
NEWFOUNDLAND AND LABRADOR REGION

present a two-day workshop

INTERSCALE RELATIONSHIPS WITHIN FOREST-ATMOSPHERE PROCESSES

to be held

August 25 - 26, 1994

in Room X-4008
S.J. Carew Building
Memorial University of Newfoundland

**THE INTERNATIONAL UNION OF FORESTRY RESEARCH
ORGANIZATIONS**

SG 1.03.00: ENVIRONMENTAL INFLUENCES ON FOREST GROWTH
AND
SG 2.01: PHYSIOLOGY

PROCEEDINGS OF AN IUFRO WORKSHOP

ON

**INTERSCALE RELATIONSHIPS WITHIN
FOREST-ATMOSPHERE PROCESSES**

Memorial

University of Newfoundland