THE ASPEN PARKLAND IN WESTERN CANADA: A DRY-CLIMATE ANALOGUE FOR THE FUTURE BOREAL FOREST?

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Abstract. Predicted future changes in regional climate under a doubling of atmospheric CO_2 concentrations were applied to the 1951–80 normals of 254 climate stations to examine future impacts on the boreal forest of western Canada. Previous analyses have indicated that in this region, the southern boreal forest is presently restricted to areas where annual precipitation (P) exceeds potential evapotranspiration (PET). The present analysis suggests that a predicted 11% increase in P would be insufficient to offset the increases in PET resulting from a predicted warming of 4–5°C. As a result, half of the western Canadian boreal forest could be exposed to a drier climate similar to the present aspen parkland zone (P < PET), where conifers are generally absent and aspen is restricted to patches of stunted trees interspersed with grassland. Future changes could result in permanent losses of forest cover following disturbance and an increase in the proportion of exposed edge habitat in remaining stands, where environmental conditions might induce additional stresses on tree growth. Thus if the predicted warming and drying occurs, productivity of aspen and other commercial species in the southern boreal forest would be greatly reduced.

Keywords. CLIMATE CHANGE, DROUGHT, EVAPOTRANSPIRATION, *Populus tremuloides*, PRAIRIE-FOREST BOUNDARY.

1. Introduction

Most of the recent General Circulation Models (GCMs) predict relatively large changes in the climate of the western Canadian interior as a consequence of increases in the levels of atmospheric CO_2 and other greenhouse gases (e.g., Houghton *et al.*, 1990). Existing climate records indicate that there has already been a significant warming of between 0.9 and 1.7 °C in this region over the past century (Gullet and Skinner, 1992). One of the greatest concerns, however, is that the small predicted increases in precipitation will be insufficient to offset the much higher evapotranspiration rates expected under a warmer climate (Zoltai *et al.*, 1991). This could lead to significantly drier soils and more severe droughts over much of this region in the future (e.g., Houghton *et al.*, 1990; Manabe *et al.*, 1992).

In western Canada, the boreal forest forms its southern boundary with the aspen parkland (Figure 1), a transitional vegetation zone characterised by patches of trembling aspen (*Populus tremuloides* Michx.) interspersed with grassland. Farther south, the aspen parkland grades into the true grassland or prairie, where trees are absent except along water-courses. Vegetation of the region is discussed in relation to ecological and historic factors by Rowe and Coupland (1984).

A recent analysis of climate gradients in the southern Prairie Provinces of western Canada (Hogg, 1994) supports previous suggestions that forest distribution is primarily limited by soil moisture deficits and recurring severe drought (e.g., Looman, 1979; Zoltai *et al.*, 1991). In that analysis, regional gradients in moisture were mapped using a climate moisture index that was based on the difference between mean (1951–80) annual precipitation (P) and annual potential evapotranspiration (PET), using the Jensen–Haise method. The southern boundary of the boreal forest was found to

Water, Air and Soil Pollution **82**: 391–400, 1995.

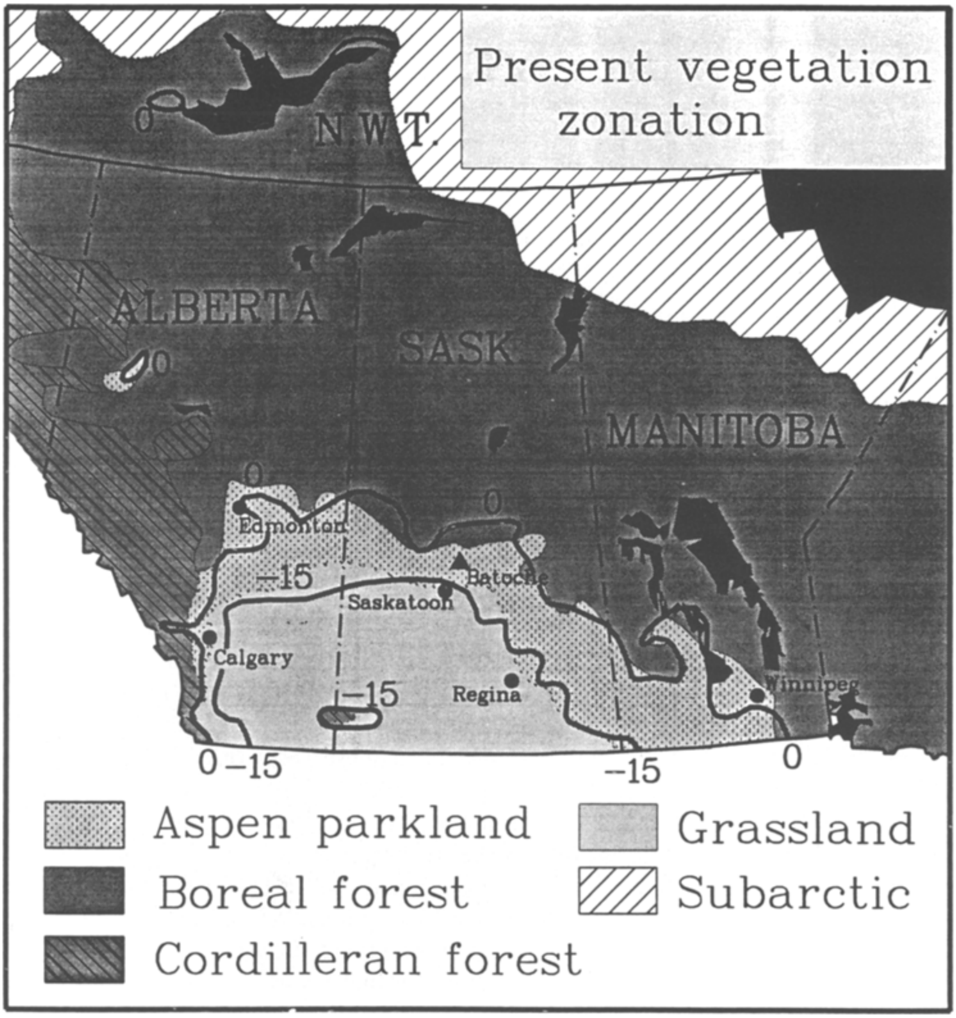

Fig. 1. Present distribution of vegetation zones in the western interior of Canada (after Ecoregions Working Group, 1989), in relation to the zero and -15 cm isolines of the P - PET climate moisture index for the period 1951–80 (after Hogg, 1994). Dry climate outliers (P - PET < 0) in northwestern Alberta (Peace River) and the Northwest Territories (Providence) are also shown.

correspond closely to the isoline where P = PET; i.e., a climate moisture index (P – PET) of zero. The analysis also showed a good correspondence between the -15 cm isoline, i.e., where P – PET = -15 cm, and the southern boundary of the aspen parkland with the grassland zone (Figure 1). The importance of moisture to the present vegetation zonation is also suggested by regional gradients in hydrological processes. In the boreal forest, the quantity of annual runoff typically ranges from 50–200 mm per year, but sharply decreases to < 25 mm per year over most of the aspen parkland and grassland zones (Figure 2). As a consequence, lake levels in the boreal forest tend to be constant from year to year, but show high interannual variability in the drier zones to the south, where lakes may dry up completely during periods of drought (Campbell *et al.*, 1994, pers. obs.). Hydrological gradients can also account for the abrupt change that occurs in a variety of ecosystem processes and characteristics at the boundary between boreal forest and aspen parkland (summarised in Table I). However, the GCM climate predictions indicate that the climate of the southern boreal forest may become warmer and drier in the future, similar to that found in the present aspen parkland. Such a change, accompanied by a northward shift in the zero P – PET isoline, would cause severe stresses on ecosystem functioning in the southern boreal forest.

The first objective of this study was to examine which areas of the western Canadian boreal forest are likely to be most sensitive to severe moisture stress under climate change. This was achieved by imposing a $2\times CO_2$ climate regime and mapping the equilibrium zonation of vegetation based on future predicted values of the P – PET index. Several GCM predictions are available; here we apply a generalised prediction for the region based on the Canadian Climate Centre GCM (Boer *et al.*, 1992). The second objective was to identify processes and characteristics of the aspen parkland zone, especially stresses on aspen under the present climate, that might serve as a climate change analogue for the most sensitive areas of the western Canadian boreal forest.

2. Materials and Methods

The predicted future climate of the western Canadian interior was based on the North American data subset of the CCC General Circulation model (Boer *et al.*, 1992), provided by the Canadian Climate Centre of Environment Canada, Downsview, Ontario. For the region bounded by 50°06'N to 61°12'N and 93°45'W to 116°15'W (28 GCM grid points), the average predicted changes in annual climate characteristics under a doubling of atmospheric CO_2 levels include a 4.2 °C increase in mean daily maximum temperature, a 4.9 °C increase in mean daily minimum temperature, and an 11% increase in precipitation. To estimate the future climate of the region, we applied these changes to the monthly climate normals (1951–1980) of 254 year-round stations in the region. Climate data sources and station locations are given in Hogg (1994).

TABLE I

Summary of differences in processes and characteristics between the boreal forest and aspen parkland in western Canada.

Characteristic	Boreal forest	Aspen parkland	Reference
Climate	P > PET (moist)	P < PET (dry)	Hogg, 1994
Coniferous trees	4–6 species	0 (1) species	Zoltai, 1975
Aspen	productive stands	stunted patches	Zoltai *et al.*, 1991
Peatlands	common	rare or absent	Vitt *et al.*, 1994
Annual runoff	50 to > 200 mm	< 50 mm	see Figure 2
Lake levels	constant	variable	Campbell *et al.*, 1994

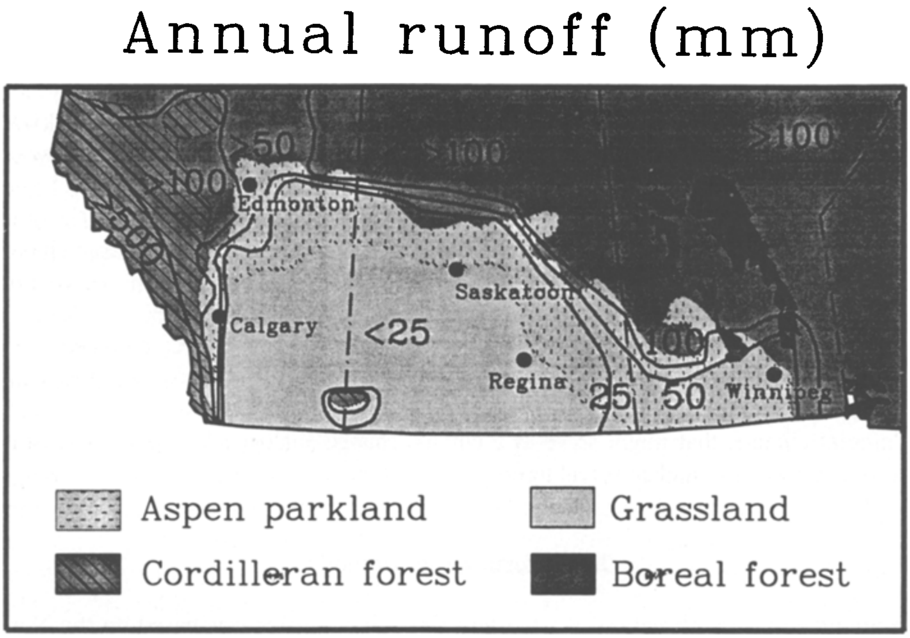

Fig. 2. Estimated annual runoff in the southern Prairie Provinces of western Canada (Alberta, Saskatchewan and Manitoba), based on Fisheries and Environment (1978). The 25, 50, 100 and 500 mm isolines are shown.

For each station, mean PET was estimated for the predicted future climate using the Jensen-Haise method (Bonan, 1989; Jensen *et al.*, 1990) as described by Hogg (1994). In the calculations of PET, it was assumed that future change in mean monthly solar radiation will be negligible. The P - PET climate moisture index under the predicted 2×CO_2 climate was determined for each station by subtracting PET from annual precipitation (P), with units in cm. The equilibrium distribution of future vegetation zonation under the 2×CO_2 predicted climate was then mapped, using the zero and -15 cm isolines of the future P - PET moisture index as follows: forest (P - PET > 0); aspen parkland (P - PET from 0 to -15); grassland (P - PET < -15). For purposes of presentation only, we used the 15 °C mean July isotherm as the approximate future position of the northern limit of the boreal forest.

3. Results and Discussion

The projected changes in the zero and -15 cm isolines of the P - PET moisture index in the western Canadian interior under a 2×CO_2 climate, as reflected by the vegetation zonation shown in Figure 3, suggest that a 4–5 °C increase in mean temperature would lead to much drier conditions in the region, despite the 11% predicted increase in precipitation (Figure 3). Based on this analysis, fully half of the present boreal forest in western Canada could develop a dry climatic moisture regime similar to the current aspen parkland (P - PET of 0 to -15 cm). The distribution of areas vulnerable to vegetation change (Figure 3) is similar to that suggested by others (e.g., Schwarz and Wein, 1990; Smith *et al.*, 1992), but our analysis takes topographic variation into account in greater detail. In general, we found that a 100 m increase in altitude resulted in a 5 cm increase in the P - PET moisture index, both because of cooler temperatures and greater precipitation (Hogg, 1994). Thus most areas of upland boreal forest (altitudes of ca. 600–1400 m) are expected to remain sufficiently moist to support forest cover under the 2×CO_2 climate. Parts of the boreal forest at lower altitudes in northern Manitoba are also relatively moist. In contrast, much of the lowland boreal forest elsewhere, might become dry enough to degrade into a mixture of forest remnants and grassland (i.e., an aspen parkland-type climate). These potentially sensitive lowlands occur over large areas adjacent to the major lakes and rivers (shown in Figure 3) across portions of northern Alberta, Saskatchewan and the Northwest Territories. The analysis suggests that climate impacts on these areas might eventually lead to an east-west fragmentation of the boreal forest in the region.

The map of future forest zonation (Figure 3) should only be regarded as an estimate of the equilibrium condition under a regionally generalised 2×CO_2 scenario, if it were to remain fixed for several centuries. The actual vegetation responses would likely be much more complex under the rapid, transient change in climate that is predicted. Schwarz and Wein (1990) point out that under climate change, rapid conversion of boreal forest to grassland may not occur until there is a major disturbance such as fire. Also, differences in plant species responses, e.g., dispersal and regeneration capacity following disturbance, may result in future vegetation types that have no modern analogue (MacDonald and Ritchie, 1985). This analysis does not consider the potential benefits of atmospheric CO_2 levels on plant water-use efficiency, which could partially offset the impacts of drought in the future (Long and Hutchin, 1991), nor does it take into account the possible negative impacts on vegetation caused by continuing increases in UV-B radiation from atmospheric ozone depletion (Kerr and McElroy, 1993; Yakimchuk and Hoddinott, 1994). Nevertheless, under the predicted future climate regime, moisture limitations could still lead to serious reductions in tree productivity within the next few decades in the more accessible, southern portions of the boreal forest in western Canada.

In the more remote, northern boreal forest and in other areas at high elevation, warmer temperatures and longer growing seasons, coupled with moist climatic conditions, might be expected to improve forest productivity in the future. However, a large proportion of these potentially favourable areas are located on the Canadian shield, where edaphic conditions are likely to remain as a constraint to tree growth in the future (Zoltai *et al.*, 1991).

Trembling aspen is the major hardwood species in the southern boreal forest of western Canada, where it has become an important commercial species for the forest industry since the late 1980s (Peterson and Peterson, 1992). For this species, the climatically warmer and drier aspen parkland zone can serve as an excellent analogue for probable growth responses under a 2×CO_2 climate. This approach forms the basis for an ongoing study (Hogg and Hurdle, unpublished) of the aspen parkland at Batoche, near Saskatoon, Saskatchewan (shown in Figure 1), as part of the Boreal Forest Transect Case Study (Price and Apps, 1995, this volume).

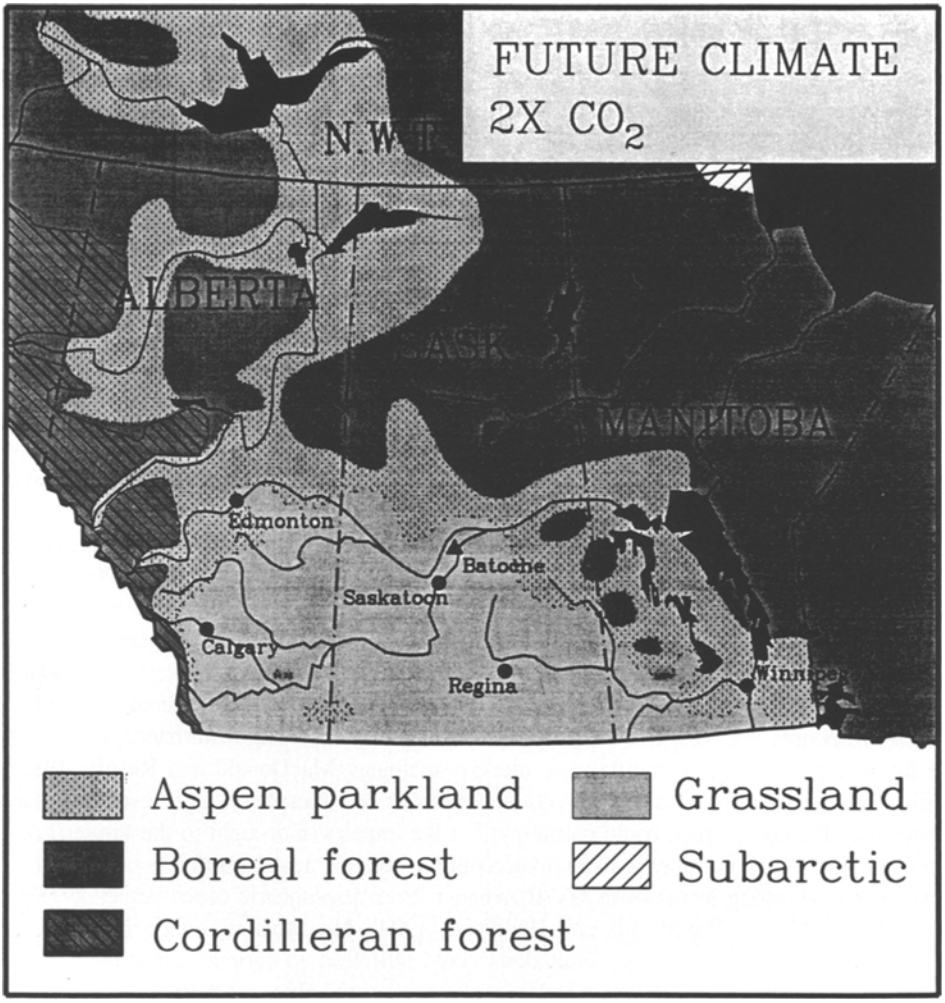

Fig. 3. Projected equilibrium vegetation, based on estimated future changes in the zero and -15 cm isolines of the P-PET climate moisture index, under 4.2 °C and 4.9 °C increases in mean daily maximum and minimum temperature, respectively, and an 11% increase in annual precipitation. New position of the northern limit of the boreal forest is based on the 15 °C mean July isotherm.

Surveys conducted at the Batoche site indicate that in this dry climate (P - PET = -13), aspen has a strongly stunted growth form and a reduced biomass productivity. For a given diameter, height growth at Batoche (Figure 4) was only about half to two-thirds that expected in the boreal forest (based on Huang *et al.*, 1992). The difference in growth form is shown in Figure 5. At Batoche, 75-year old aspen had achieved a height of only 12–14 m and estimated stand basal area of 15 m^2 ha^{-1} (mean of 24 prism sweeps), compared to the ca. 18 m and 25 m^2 ha^{-1} reported by Kirby (1975) for "poor sites" in the boreal forest of Saskatchewan. Similar comparisons have been made by Maini (1968) and by Johnstone and Peterson (1980), giving an indication of the impacts on aspen productivity that might be

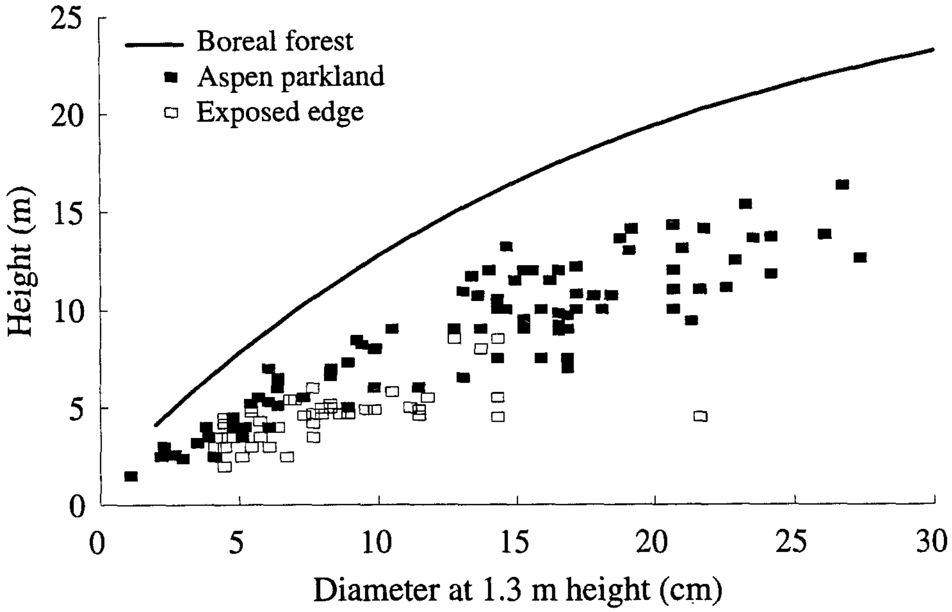

Fig. 4. Height-diameter relationships for trembling aspen (*Populus tremuloides*) in the boreal forest (equation 4 of Huang *et al.* 1992); and the aspen parkland at Batoche, Saskatchewan (authors' measurements) for forest interior sites (solid symbols) and exposed sites within 20 m of a forest-grassland edge (open symbols).

expected in the southern boreal forest under climate change. Furthermore, tree ring analyses on aspen at Batoche (Hogg, unpublished) indicate that radial growth is reduced by up to 90% during severe drought periods. Insect defoliators, such as the forest tent caterpillar (*Malacosoma disstria*), and numerous fungal species impose additional stresses on aspen (Peterson and Peterson, 1992). Some are promoted by warm, dry conditions (Ives, 1981) and thus their negative impacts on productivity and wood quality might be expected to increase under a $2\times CO_2$ climate.

Severe drought, coupled with insect or disease infestations, can also lead to extensive mortality of aspen groves, as occurred over large areas of the aspen parkland in 1961 (Zoltai *et al.*, 1991) and again following the 1988 drought (pers. obs.). However, the clonal nature of aspen, and its ability to resprout vegetatively following fire or drought would make this species well-suited to persist under a drier future climate in the boreal forest. In contrast, conifers lack such an effective means of vegetative regeneration. If climate change leads to increased fire frequencies in the future boreal forest (Flannigan and Van Wagner, 1991), conifers could be gradually eliminated if they are burned before reaching a seed-bearing age (ca. 30 years), or if soil conditions become too dry for successful seedling establishment (Hogg, 1994). The area affected by fire in Canadian forests increased dramatically under the dry conditions of the 1980s, notably in 1989 when fires burned over 3 Mha of boreal forest in northern Manitoba (Hirsch, 1991). In the Nisbet Forest, located 100 km north of Saskatoon, Saskatchewan, poor regeneration of jack pine (*Pinus banksiana* Lamb.) following one of the 1989 fires has lead to stand conversion to aspen and grassland in some areas (S. Hyde, Saskatchewan Forestry Branch, pers. comm.).

One of the main characteristics of the aspen parkland is that the trees are typically restricted to numerous small groves or "bluffs", often interspersed with large expanses of grassland. As a result, a high fraction of the aspen stems are located in exposed, edge habitat where environmental conditions can be substantially more severe than in the interior of larger areas of forest. This often results in even more pronounced stunting of aspen height in relation to diameter as shown in Figure 4 for exposed aspen at Batoche. In these situations, the aspen often develop crooked, leaning or forked stems (Figure 5). Measurements taken from June to September 1994 at the Batoche site indicate that aspen crowns at a grassland edge experienced 5 times greater mean wind speed than in the forest interior, located 300 m away from the edge. Furthermore, in-canopy vapour pressure was 6% lower and vapour pressure deficit was 11% greater at the edge compared to the forest interior during the same period (Hogg and Hurdle, unpublished). These and other differences in microclimate appear to control the differences in aspen growth form, although the precise mechanisms are not yet understood.

4. Conclusions

The present analysis suggests that climate change could have a major impact on moisture regimes and the future distribution of the southern boreal forest in western Canada. In areas where the forest becomes fragmented into small patches, either through natural processes or as a result of forest harvesting, a higher proportion of trees would occupy edge habitats with an even greater exposure to environmental stress, leading to stunted growth.

Acknowledgments

We thank S.C. Zoltai at the Northern Forestry Centre, and two anonymous reviewers for useful comments on the manuscript. This study has been supported by Green Plan funding (NOR-1683) within the Department of Natural Resources Canada.

Fig. 5. Growth form of 75-year old aspen stands in (left) the boreal forest in Prince Albert National Park (53°38'N, 106°12'W) and (centre) in the aspen parkland at Batoche (52°44'N,106°09'W). Also shown (right) are 30-year old aspen in an exposed, grassland edge site at Batoche. All photos were taken in mid-October following leaf-fall.

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