Growth form adaptations by conifers in an anthropogenically stressed environment, Flin Flon, Manitoba - preliminary observations

Geoffrey A. J. Scott and Gregory M. J. Scott,
University of Winnipeg

Abstract: Growth form adaptations by conifers to harsh climates are the norm in such places as the alpine treeline and the forest-tundra/tundra transition. Here, various shapes of krummholz, such as mats, basal skirts (rosettes), and flag development, together with vegetative propagation by way of layering, are typical adaptations to low temperatures, desiccating winds, and ice-crystal blasting. This study reports preliminary data and analysis of similar adaptations by black spruce and jack pine in a climatically less stressed mid-boreal ridge-crest environment near the Hudson Bay Mining and Smelting Co. smelter in Flin Flon, a region now severely impacted by air pollution. Undisturbed shield ridge-crest ecosystems some distance from Flin Flon consist of somewhat open jack pine and black spruce stands with cryptogam (lichen-moss) ground cover. Near the smelter SO_2 and metal particulate have severely impacted ridge-crests to the point that their cryptogam cover has died and their thin organic-cryptogam soils have been badly eroded. This has exposed bedrock and caused most of the ridge-crest conifer tree cover within three km of the smelter to die off. Pollution-induced thinning of ridge-crest ecosystems decreases progressively away from this zone. Surviving conifers close to the smelter are exposed to the effects of reduced volumes of sustaining soil, soil pollutants, exposure to greater wind speeds, and supranival exposure to winter fumigation. For black spruce this has induced krummholz forms such as mats, development of basal skirts, and often signs of supranival flagging and deformation similar to those characteristic of the alpine treeline and the forest-tundra/tundra transition. Many jack pine exhibit basal skirt formation, with some surviving only as mat krummholz, as is the case for many pine species along the alpine treeline in western North America.

Key words: pollution, ridge-crests, cryptogams, growth forms, black spruce, jackpine

Introduction

Growth-form adaptations by conifers to stress are particularly evident in the forest-tundra/tundra transition of the high subarctic, and along the transition between the alpine treeline and alpine tundra. At both locations spruce growth-form adaptations are attributed to the extreme climate and impacts of desiccating winds, while ice-crystal abrasion and damage of needles is also a major contributing factor in the high subarctic. Along the forest-tundra/tundra transition white and black spruce (*Picea glauca* and *P. mariana*) and tamarack (*Larix laricina*) show modifications to these extreme conditions (Scott, 1995). At alpine treeline in the western cordillera species such as Engelmann spruce (*Picea engelmannii*), subalpine fir (*Abies lasiocarpa*), limber pine (*Pinus flexilis*) and lodgepole pine (*P. contorta*) are affected (Weisberg and Baker, 1995). For both regions the classic physiognomic conifer growth form often becomes modified to form krummholz ('crooked wood') shapes. Typical modifications include mat krummholz, basal skirts (rosettes), and 'flag' forms. Basal skirts (rosettes) develop and survive because branches close to ground level are better protected within the winter snow (infranivally). Stems projecting above snow level (supranival) are exposed to wind and ice-crystal blasting and can develop flagged or otherwise deformed krummholz shapes, or die-back leaving only infranival krummholz forms. Figure 1 illustrates typical growth form adaptations for white spruce (*Picea glauca*) near Churchill (Scott *et al.*, 1987) and by black spruce (*Picea mariana*) in northern Quebec (Lavoie and Payette, 1992).

In 1989 field studies on severely impacted ridge-crest ecosystems near the point-pollution source of the Hudson Bay Mining and Smelting Co. (HBMS) smelter in Flin Flon revealed somewhat similar adaptations by black spruce, and jack pine *(Pinus banksiana*). This was considered anomalous because here the natural vegetation cover is characteristic of the mixed-woods section of the boreal forest, and bio-climatically as part of the 'sub-humid mid-boreal ecoclimatic region' (Scott, 1995). Typical tree species include such hardwoods as trembling aspen (*Populus tremuloides*), black poplar *(P. balsamifera*), and paper birch (*Betula glandulosa*), together with softwoods such as white and black spruce and jack pine. Rowe (1972) describes this mixture of hardwoods and softwoods as the 'mixed-woods' section of the boreal forest, and attributes the mix to frequent fires that are encouraged by the sub-humid forest climate. For Flin Flon the mean annual temperature is 0.6˚C with seven months averaging above zero, and mean annual precipitation is 463.1 mm (Environment Canada, 2002). Mean annual snowfall is 140 cm, and dominant winter winds are towards the southeast (Franzin, *et al.*1979).

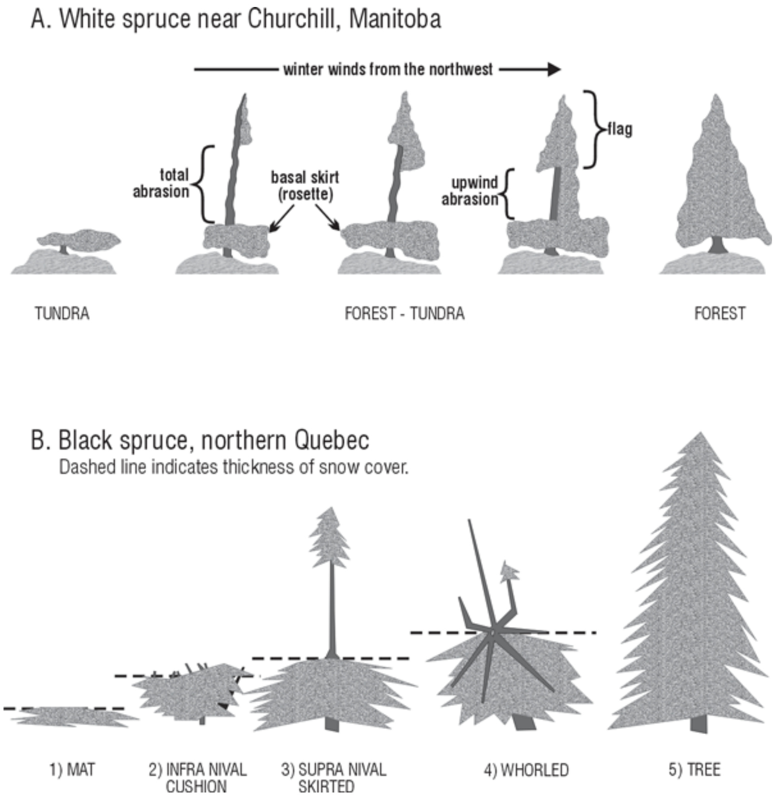

Figure 1: *Spruce growth forms across the forest-tundra/tundra transition. A. White spruce near Churchill (adapted from Scott* et al.*, 1987). B. Black spruce, northern Quebec (adapted from Lavoie and Payette, 1992).*

Objectives

In 1995 new field studies were initiated to determine the types of growth form modifications present in the heavily polluted zone close to Flin Flon. In addition, a preliminary investigation was initiated to see if those conditions which promote such modifications in the climatically more extreme high subarctic and alpine treeline also give rise to growth form modifications near Flin Flon.

The Study Region

Flin Flon is located on a portion of the PreCambrian Shield containing orebodies rich in non-ferrous metals (Figure 2A). Shield outcrops form low rolling hills with glacially scoured crests that have been scraped relatively clean of regolith (Figure 3). HBMS began smelting for zinc and copper in 1930. Emissions were released to the atmosphere from a single 30 m tall stack. This stack was replaced in 1974 by one 251 m tall. Emissions include sulfur dioxide, zinc, cadmium, copper, arsenic, and other base metals, with dry and wet base metal fallout taking the form of metal particulate, and metal oxides and metal sulfates (Franzin *et al.* 1979). The dominant winds have given rise to an oval pattern of decreasing base-metal contaminated soil centered on Flin Flon, with a northwest to southeast axis (Zoltai 1988). These pollutants have lead to tree and groundcover mortality on ridges, and to epiphytic and terricolous cryptogam cover in the lowland depressions. For more detailed information on both pollution loads and impacts to vegetation near Flin Flon see, Hogan and Wotton (1984), and Scott (2000).

Undisturbed ridge crests some distance from Flin Flon include soil-free areas (but with terricolous cryptogam cover) and thin Folisol-like organic profiles developed from dead cryptogams, and conifer and herbaceous plant residues. These Folisols are protected from erosion by the living cryptogam and vascular plant cover and provide an acidic substrate sufficient to support scattered jack pine. Where Folisols are underlain by a thin veneer of mineral soil, black spruce have become established. Consequently, undisturbed ridge-crests often contain a mix of both jack pine and black spruce. Closer to the smelter these plant communities are missing or are damaged as cryptogam death leads to the dessication and erosion of the thin Folisols and mineral soil veneers. Cryptogam regeneration seldom occurs, and the surface is essentially a sterile grey-black colour with only the occasional vascular species such as blueberry (*Vaccinium angustifolium*), colonial bentgrass (*Agrostis capillaris*), and willow (*Salix* sp.) showing any signs of vigor (Figure 3).

Methods and Materials

Study site selection:

In 1989 and 1995 fourteen ridge-crest study sites were selected throughout the region to study the impacts of atmospheric pollution on ridge crest ecosystems (Figure 2). Sites #1-10 follow a southeast transect of decreasing pollution load downwind of the smelter to Cranberry Portage.

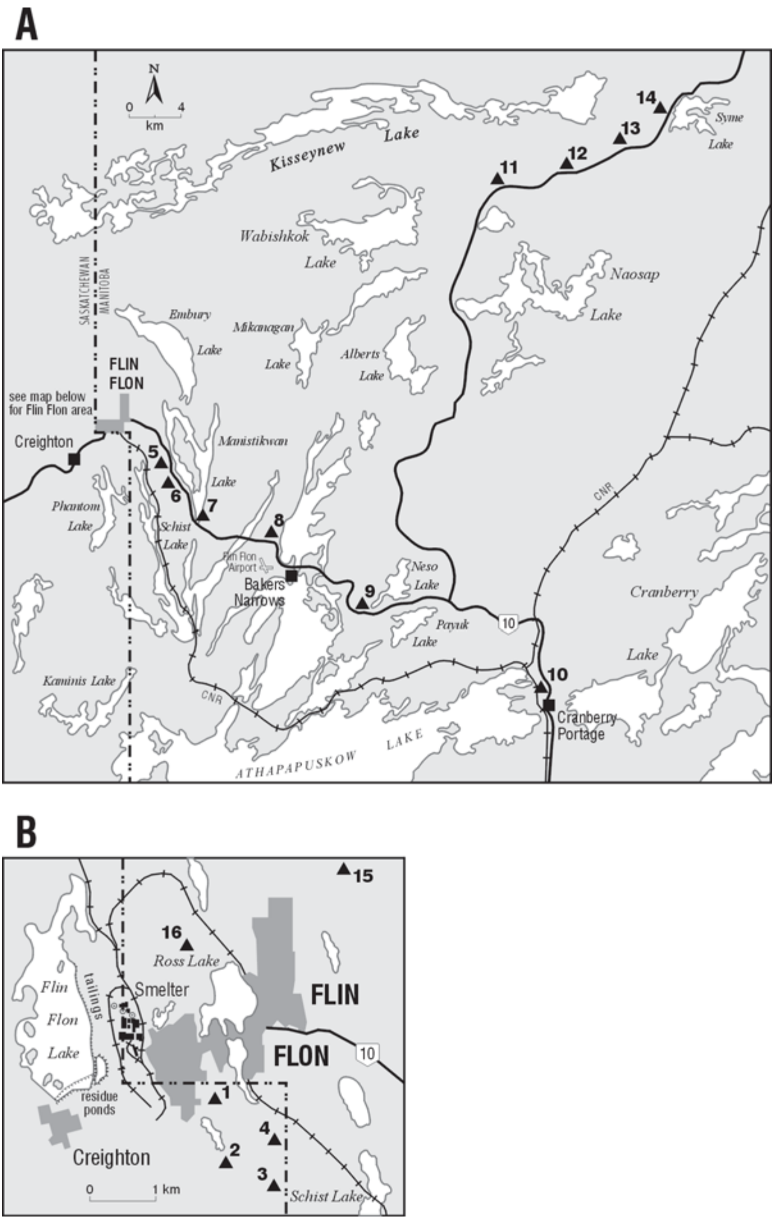

Figure 2: *The Flin Flon, Manitoba, study region. A. Study Sites more than 4 km from the HBMS smelter. B. Study sites within 4 km of the HBMS smelter.*

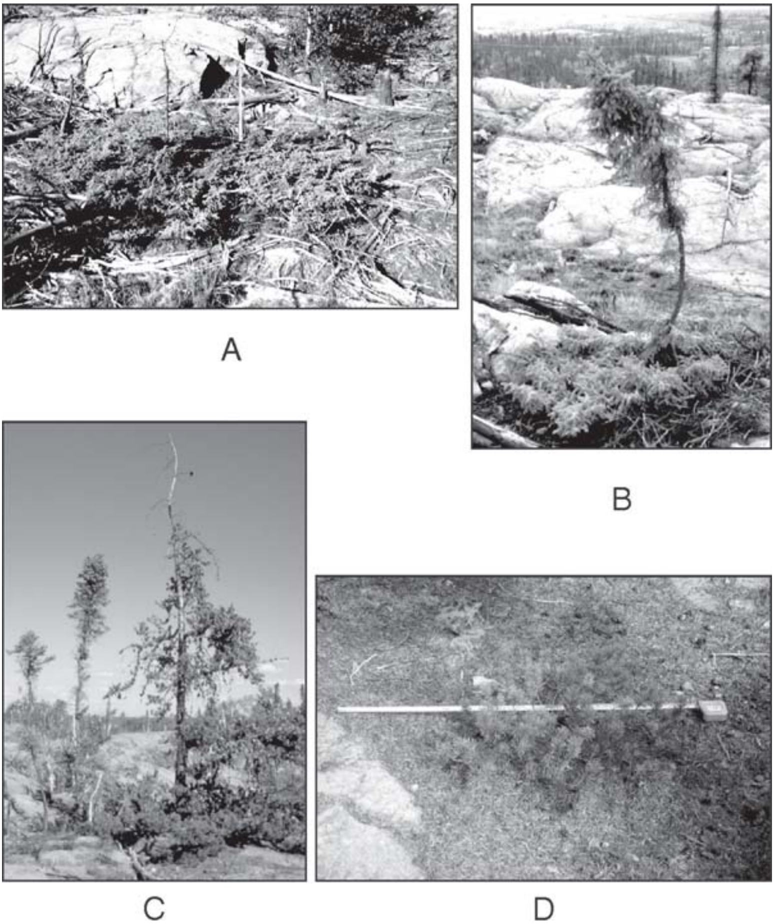

Figure 3: *Growth form adaptations by black spruce and jack pine close to Flin Flon. Note the lack of ground cover. A = mat krummholz black spruce; B = supranival skirted black spruce; C = supranival skirted jack pine; D = mat krummholz jack pine.*

As suitable study sites could not be selected southeast of Cranberry Portage, due to the fact that here carbonate bedrock replaces igneous and metavolcanic bedrock, four control sites (11 - 14) were selected to the northeast along the Sherridon road where no visible air pollution impacts were observed, and where soil base-metal contents approach background levels (Zoltai, 1988). In addition, in 2002 two additional sites (15 and 16) were selected just north and northeast of the smelter, because at these sites jack pine showed well developed growth form adaptations. Specific field studies to characterize these adaptations were carried out at selected study sites in the summers of 1995, 1996 and 2002, and in the winter of 1996. For specific details on pollution-induced thinning of ridge-crest ecosystems along the transect from Cranberry Portage to Flin Flon (Study Sites 1 - 10) see Scott and Orlandini (2002).

Growth form sampling:

Due to the preliminary nature of this study only some of the non-impacted control sites, and most severely impacted sites were sampled. At vegetated ridge-crest control Study Sites 12 and 14, quadrats of 20 x 20 m were established to sample black spruce and jack pine. Closer to the smelter, severely impacted Sites (2 and 3) were also sampled for black spruce using 50 x 50 m quadrats to allow for sufficient living trees to be studied. Sampling was not possible at Study Site 1 as no living conifers remained there. Jack pine were sampled at Study Sites 15 and 16 using 50 x 50 m quadrats. In addition, pine were sampled in Study Site areas 2 and 3, but because there were so few surviving pine here the quadrat combined both site regions and covered 1.75 km^2. All black spruce and jack pine trees within a quadrat were measured for height, and where living branches exited trunks close to ground level and above basal skirts, flagging characteristics and aspects of supranival die-back. For basal skirts, both skirt depth, and skirt branch length from stem along the eight cardinal compass directions were measured. In addition, mat krummholz forms were documented, and any vertical stems growing from windthrow or from basal skirt branches (*i.e.* layering) were noted.

Results

1. Black Spruce:

While no living conifers remain on the sterile rock outcrops at Study Site 1, the most severely impacted study site, an important observation is that tall, healthy white spruce, showing no signs of flagging or basal skirt development, are present in Flin Flon ridge-crest gardens several hundreds of metres away. In these gardens the soil is anthropogenic and well maintained, and other garden trees afford some protection from the wind. In addition, both black and white spruce survive with few growth form modifications on the deep mineral and organic soils of lower slopes and lowlands below the study sites. Study Sites 2 and 3 are severely impacted sites which support some scattered living spruce and the occasional pine. At these two sites, black spruce average 5.9 m tall, and individuals are rarely clumped so branch die-back due to shading is not expected (Table 1). Mat krummholz and basal skirt forms hug the ground closely, are typically no more than 35 cm thick, have irregular margins, and do not show the oval pattern so characteristic of spruce skirts in the high subarctic (Table 2, Figure 3A and 3B). Occasionally layered branches have new vertical stems rising from them, and basal skirts often have more living needles than on the few remaining supranival branches above. In addition, flag forms are fewer and less symmetrical than the classic forms illustrated in Figure 1, yet often the northwest side facing the smelter exhibits less vigorous growth and fewer living branches. The branchless zone between basal skirts and the first living supranival branch averages about 2 m (Table 3). Winter snow depths at these two sites averaged 30 cm in February, 1996. Consequently, skirts were well protected during winter inversion/ fumigation episodes. Equivalent 1996 snow depths around the more closely spaced trees at Sites 8 - 10 were 90 - 95 cm, and although some individuals had branches hugging the ground, there was no branchless zone separating these from supranival branches above. Observations on needles in these

Table 1: *Black spruce stem/branch characteristics close to Flin Flon.*

study site[1] #	# of living trees used	mean tree height (m)	trees with basal skirts	# of mat krummholz spruce	new stems from skirt	mean skirt thickness (cm)	mean[2] skirt branch length (cm)
2	19	5.7	16	2	4	34.3	94.3
3	9	6.4	7	0	1	33.9	73.4

1. Quadrats = 50 X 50 m.
2. Mean of basal skirt branch lengths measured along eight cardinal compass directions.

Table 2: *Black spruce mean basal-skirt branch length (cm) and branch orientation close to Flin Flon. Smelter is to the NW of both sites.*

study site[1] #	# with basal skirts	N	NE	E	SE	S	SW	W	NW	mean branch length (cm)
2	16	98.3	91	100	99.4	94.7	82.9	91.3	96.6	94.3
3	7	75.8	53	66	83.4	90.4	88.3	73.4	57	73.4

1. Quadrats = 50x50 m.

Table 3: *Supranival characteristics of black spruce close to Flin Flon.*

Study site[1] #	# of living trees	# with a branchless zone[2]	length of branchless zone (m)	# of flagged trees	# with branch thinning[3]	relative % of branch thinning[4]
2	20	12	1.87	3	7	28
3	7	7	2.85	4	2	25

1. Quadrats = 50 X 50 m.
2. A branchless zone between ground or basal skirt (if present) and the first supranival living branch.
3. One side of tree (not necessarily flagged) but with fewer and shorter living branches, and oriented towards smelter.
4. Relative percentage of branch thinning for trees in note # 3.

lower zones showed little indication of cuticle rupture from ice-crystal blasting. Tree cores revealed that most black spruce colonized these sites since the smelter became operational in 1930. Figure 4A summarizes black spruce growth forms found present in the heavily impacted zone close to Flin Flon.

2. Jack pine:

Although jack pine close to the smelter usually have basal skirts, these are not always as dense and as symmetrically disposed abound the tree base as with black spruce, having only 2 - 6 basal branches. Although mean skirt branch length is approximately 1 m, some regularly exceed 2 m (Figure 3C), with one at Study Site 16 reaching 4.5 m. Jack pine trunks are shorter than for remnant black spruce, averaging only 4.65 m, and with branchless zones between skirts and the first supranival living branch of about 1 m (Table 4). Basal skirt shapes shows little symmetry and any geographic orientation seems influenced more by nearby rocks and outcrops than by prevailing winds. Flagging rarely seemed to be a significant modification to jack pine near Flin Flon.

At control Study Sites 12 and 14, few basal branches are found. Individual trees are much taller, closely spaced, and possess some dead lower branches typically associated with shading. Layering is uncommon, except for surviving windthrow. There is little evidence of needle cuticle damage from ice-crystal blasting. Figure 4 B summarizes jack pine growth forms found close to the smelter.

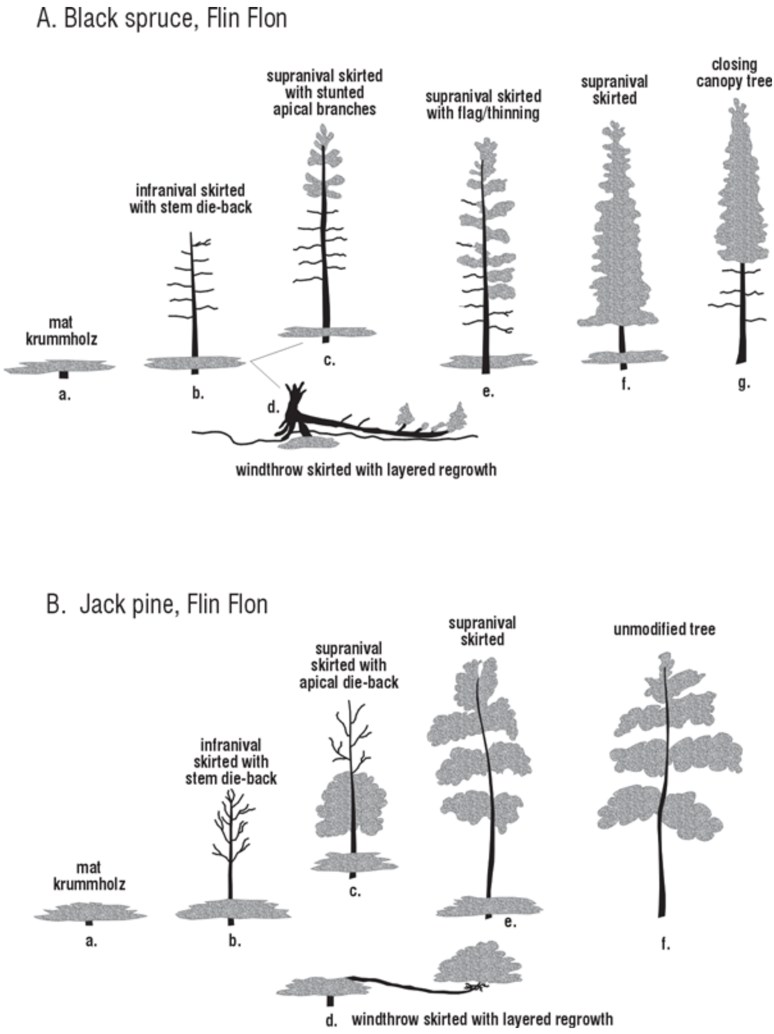

Figure 4: *Typical growth-form adaptations by black spruce and jack pine on ridge crests close to the Flin Flon smelter.*

Discussion

Growth form adaptations by black spruce and jack pine are important survival strategies for isolated individuals surviving on ridge crests near Flin Flon. It would appear from this preliminary study that black spruce adaptations result primarily from the impact that air pollution has in opening

Table 4: *Selected Jack pine characteristics at four sampling sites close to Flin Flon.*

Study site[1] #	# of trees used	mean height (m)	# of krumm-holz	# with basal skirts	mean skirt thickness (cm)	length[3] of branchless zone (m)	# of trees with apical stem dieback	# of trees with skirt verticals
2+3	5 [2]	8.5	0	2	32	2.7	2	0
15(a)	18	3.35	0	17	25	0.85	0	0
15(b)	27	5.03	5	16	28	0.98	2	1
16	11	4.12	1	10	33	0	0	1

1. Only five jack pine exceeding 1 m in height were found in an area of 1.75 km^2 combining sites 2 and 3, while quadrat size for sites 15(a), 15(b), and 16 is 50 X 50 m.

2. Two of these five had apical-stem dieback of 2.0 and 2.5 m above living supranival branches.

3. A zone above ground or basal skirt (if present) before the next living branch.

up these ridge-crest ecosystems to greater dessication by winter winds and perhaps some ice crystal blasting. Increased spring/summer moisture stress as the moisture storage capacity of soil pockets continues to be reduced may also be a factor. Individual trees become isolated as die-off follows the loss of cryptogam cover and associated Folisols. Surviving or germinating ridge-crest black spruce are now confined to small patches of remnant soil, and any attempt to colonize the intervening exposed bedrock areas which would lead to reduced dessication, is impossible. In addition, stronger ground-level winter winds due to tree isolation leads to a much thinner winter snow pack and therefore a potentially reduced spring soil moisture supply. The trapping of winter snow by basal branches favors basal skirt development, while supranival stems/trunks experience damage that is partially the result of desiccating winds and dessication in general as continued erosion causes soil volume to decrease. Needle cuticle damage, which is considered a major aid to dessication in the high subarctic, is less evident here. While the dramatically-flagged spruce form so common along the forest-tundra/tundra transition and subalpine treeline is less frequently encountered here, the unequal development of branches on the side of trunks facing the smelter is similar to the characteristics of less damaged spruce in the high subarctic.

It is not possible to compare adaptations by jack pine to pine in the forest-tundra/tundra transition zone, because none are found there. Comparisons, however, can be made with pine along the alpine treeline areas of western North America where such species as, whitebark (*Pinus albicaulis*), limber (*P. flexilis*), bristlecone *(P. artistata*), and lodgepole pine (*P. contorta*), are common as krummholz and deformed and flag types (Tranquillini, 1979; Weisberg and Baker, 1995). The various jack pine growth forms found near Flin Flon are illustrated in Figure 4B, and their development not only reflects many of the same ecosystem disturbance factors noted above for black spruce around Flin Flon, but also the winter moisture stress conditions so prevalent along the alpine treeline (Tranquillini, 1979). This moisture stress southeast of Flin Flon is so profound that few pine survive, and it is noted that of the five remaining jack pine examined around Study Sites 2 and 3 (Table 4), all have overcome some of this moisture stress by having roots extend downslope to nearby semi-permanent wet depressions.

Conclusion

Atmospheric pollutants indirectly set the stage for growth form adaptation by ridge-crest black spruce and jack pine near Flin Flon (Figure 4). By damaging and destroying the ridge-crest cryptogam cover, soils are then partially or wholly eroded, mineral cycling regimes are altered, and the sustaining soil medium for trees and most plant species is severely compromised. This results in the almost total demise of cryptogams and vascular species in these ecosystems. While surviving and germinating conifers in the most heavily polluted zone must now contend with these indirect consequences of air pollution, a possible, but unknown role may also be played by air pollutants impacting directly on conifer needles, branches, and roots. One avenue for further research in this regard could be a study of possible damage to conifer-root symbiotic ectotrophic mychorriza. Given that well maintained ridge-crest garden spruce throughout Flin Flon do not exhibit these modifications, a second avenue for research could examine supranival stem and branch die-back on exposed ridge-crest spruce as related to winter-time air pollution acting preferentially on already highly stressed trees. In terms of growth form change with distance from the smelter any future study could also sample conifers at all study sites between Flin Flon and Cranberry Portage.

It is evident that indirect and possibly direct impacts of air pollutants in effect superimpose forest-tundra/tundra, and alpine treeline like conditions on black spruce surviving on these highly disturbed mid-boreal ridge crests near Flin Flon. These same impacts also impose essentially alpine treeline conditions on ridge-crest jack pine. While Tranquillini (1979) and others attribute conifer growth form modifications along the alpine treeline almost entirely to winter climate conditions, it is clear that other factors must be considered in explaining conifer growth form modifications near Flin Flon.

Acknowledgements

We thank Weldon Hiebert for his expert cartography and poster design, Sara Scott for her editing, and Brad Russell who supervised the printing of the conference poster which accompanied this paper. The University of Winnipeg is thanked for financial support.

References

ENVIRONMENT CANADA 2002 *Canadian Climate Normals 1971-2000* *http://www.msc-smc.ec.gc.ca/climate/climate_normals/results_e.cfm*

FRANZIN, W., McFARLANE, G., and LUTZ, A. 1979 'Atmospheric fallout in the vicinity of a base metal smelter at Flin Flon, Manitoba, Canada' *Environmental Science and Technology* 13: 1513-1522

HOGAN, G., and WOTTON, D. 1984 'Pollution Distribution and Effects in Forests Adjacent to Smelters' *Journal of Environmental Quality* 13(3): 377-382

LAVOIE, C. and PAYETTE, S. 1992 'Black spruce growth forms as a record of a changing winter environment at treeline, Quebec, Canada' *Arctic and Alpine Research* 24: 40-49

ROWE, J. S. 1972 *Forest Regions of Canada* (Ottawa: Canadian Forestry Publication no. 1300. Department of the Environment)

SCOTT, G. 2000 'Soil acidity (pH) as influenced by point-source pollution from a base-metal smelter, Flin Flon, Manitoba' *Prairie Perspectives* 3: 97-110

SCOTT, G. 1995 *Canada's Vegetation: A World Perspective* (Montréal: McGill-Queen's University Press)

SCOTT, G., and ORLANDINI, R. (2002) 'Rock-outcrop ecosystems as influenced by point-source pollution from a base-metal smelter, Flin Flon, Manitoba' *Prairie Perspectives* 5: 161-173

SCOTT, P., BENTLEY, C., FAYLE, D., and HANSELL, R. 1987 'Crown forms and shoot elongation of white spruce at the treeline, Churchill, Manitoba, Canada' *Arctic* 46: 316-323

TRANQUILLINI, W. 1979 *Physiological Ecology of the Alpine Timberline* (New York: Springer-Verlag)

WEISBERG, P. and BAKER, W. 1995 'Spatial variation in tree seedling and krummholz growth in the forest-tundra ecotone of Rocky Mountain national Park, Colorado, U.S.A.' *Arctic and Alpine Research* 27: 116-129

ZOLTAI, S. 1988 'Distribution of base metals in peat near a smelter at Flin Flon, Manitoba' *Water, Air and Soil Pollution* 37: 217-228