The Cause of Dieback of Coniferous Trees Near the Forest Line of Baseline Mountain, Alberta

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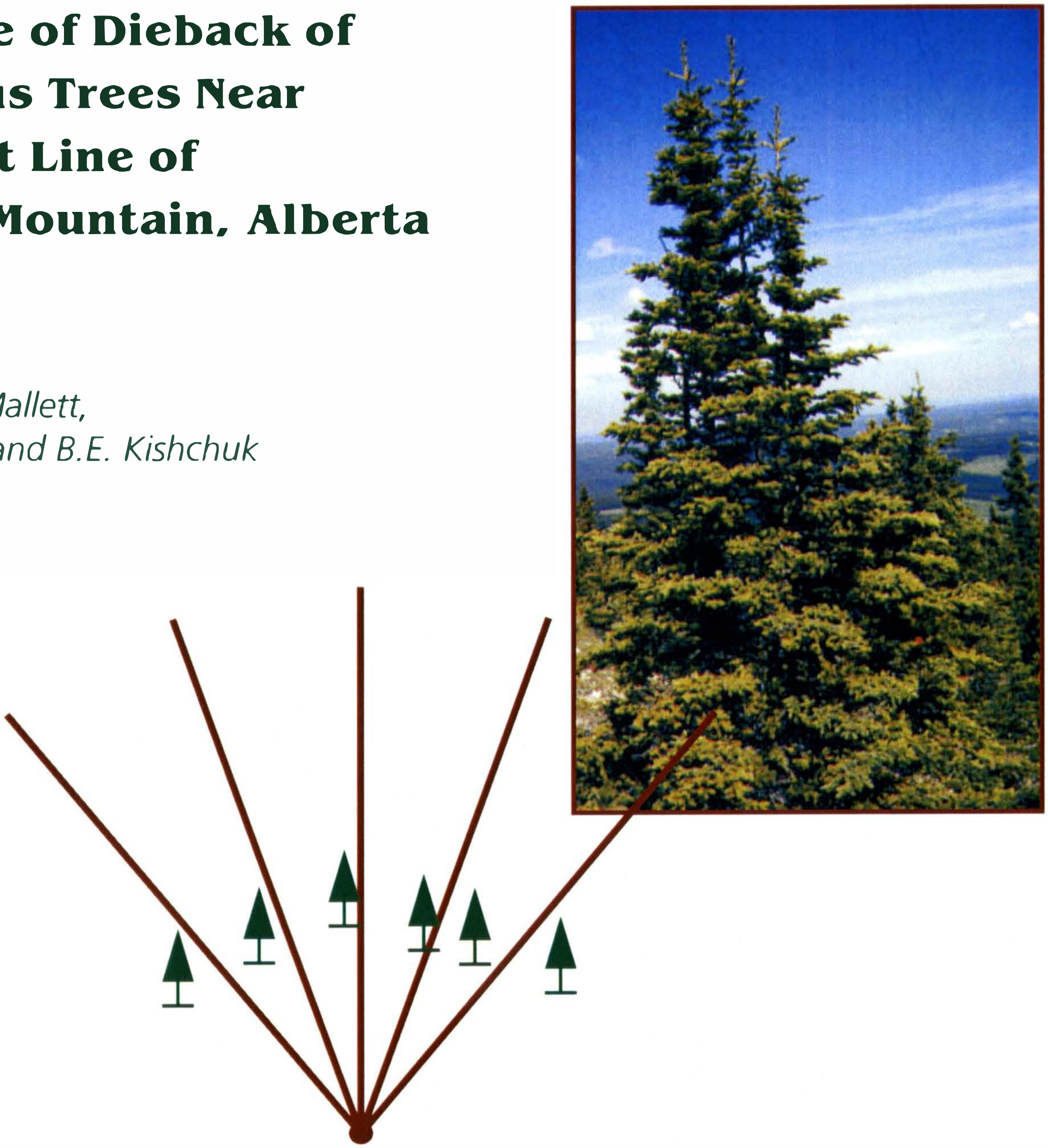

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THE CAUSE OF DIEBACK OF CONIFEROUS TREES NEAR THE FOREST LINE OF BASELINE MOUNTAIN, ALBERTA

A Report to
Husky Oil Operations Limited

W. Davis, K.I. Mallett, W.J.A. Volney, and B.E. Kishchuk

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EXECUTIVE SUMMARY

Dieback of coniferous trees near the forest line of Baseline Mountain, west of the Husky Ram River sour gas plant, was observed in 1996. This study was undertaken to determine if the dieback was caused by sulfur dioxide (SO_2) emissions from the plant or by natural disturbances such as pests or adverse climate. The Baseline Mountain site was compared to a control site on Limestone Mountain, southwest of Baseline Mountain in a zone subject to low sulfur emissions. Each site is located at a high elevation and is centered on a treeless, wind-scoured ridge with a distinct forest line marking the local elevation limit of the forest stands. Five permanent transects measuring 2 × 200 m were set up, radiating downhill from a center point located within the wind scoured area. Tagged trees were measured, and tree health was assessed. Soil, forest floor (LFH horizons), and foliage were sampled and analyzed for sulfur concentration. Stem analysis was done on trees selected from the forest adjacent to the permanent transects and on trees from similar sites on the other side of each mountain. Microclimate stations were deployed at the plot centers. Average concentrations of SO_2 in air for the winters of 1998/1999 and 1999/2000 were 1.4 and 0.9 ppb for Baseline and Limestone mountains, respectively. The mean sulfur (S) concentration in snow was not significantly different for the two sites in 1998/1999 (0.28 and 0.21 mg/L, respectively); however, in 1999/2000 it was 0.28 mg/L at Baseline Mountain and 0.06 mg/L at Limestone Mountain. There were no differences in S concentrations in soil, LFH horizons, or foliage, and the pH of the Limestone Mountain soil was significantly less than that of the Baseline Mountain soil. The microclimate of the two sites appeared similar: significant storms in the winters of 1998/1999 and 1999/2000 affected both sites. Stand structure was similar, and both sites were dominated by lodgepole pine with spruce–fir understory; however, the Baseline Mountain stand was older than the Limestone Mountain stand, which had regenerated after a fire. The tree health survey revealed that over 95% of the trees at both sites were healthy. Stem analysis revealed that the growth of pine at the two sites had declined sharply in 1968, a year in which, according to the Canadian Forest Service Insect and Disease Survey, red belt was prevalent. The specific volume increment growth loss 10 yr after 1968 was 77.4% at Baseline Mountain, and at the time of this study the trees had still not recovered to previous growth rates. The two sites were remarkably similar, both physically and ecologically. The lack of significant differences in S concentrations in soil and foliage and the lack of foliar symptoms and damage suggest that trees growing at the Baseline Mountain site have not been damaged by elevated sulfur levels. Growth losses occurred 4 years before the Ram River plant began operations; thus, the growth loss signal in the tree-ring record must be attributed to other natural factors, such as red belt. Studies on epicuticular wax of white spruce, both planted and naturally occurring, showed that there was no difference between Baseline and Limestone mountains in epicuticular wax loss over the winter. There was a statistically significant difference in the loss of epicuticular wax between trees that were growing at or above the forest line and those growing in the forest below forest line at both sites. Trees growing below forest line had a greater amount of wax after the winter than those growing at or above forest line. White spruce seedlings planted above forest line at both sites were dead after the winter.

The evidence gathered in this study indicates that reddening of foliage and dieback of trees at the forest line at Baseline Mountain was probably unrelated to SO_2 emissions. The damage was most likely caused by natural phenomena.

NOTE

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INTRODUCTION

Dieback or flagging (reddening of foliage on some branches) of coniferous tree species was observed close to the forest line (zone where continuous forest stops and isolated islands of trees begins) on Baseline Mountain, about 7 km west of the Husky Ram River sour gas plant and 25 km southwest of the Gulf Strachan plant, in 1996. There was some concern that this dieback might have been due to sulfur dioxide (SO_2) emissions from the Ram River plant. Previous studies (Addison et al. 1984; Legge, Corbin, and others 1988; Maynard 1990; Maynard et al. 1994) showed no evidence of widespread regional effects caused by SO_2, but Maynard et al. (1994) found significant damage to vegetation from elemental sulfur (S^0) dust within 2 km of sulfur blocks. The location of the damage on Baseline Mountain was well outside the 1-km S^0 deposition range. Therefore, it is likely that any impact from the Husky Ram River plant would be related to SO_2 emissions. In fact, dispersion models that use ambient climatic conditions to predict air quality at distances from the Ram River emission source have highlighted Baseline Mountain as the location that would receive the highest concentrations of SO_2 (Alberta Energy Conservation Board 1989).

The site of the dieback on Baseline Mountain was located near the forest line in a naturally occurring wind-scoured area. Trees at this site showed evidence of an alteration in normal symmetrical growth known as "krummholz." This condition is caused by wind and blowing ice crystals. It is well known that adverse climate can damage trees (Friedland et al. 1984; Harrington 1986; Hadley and Amundson 1991; Herrick and Friedland 1991), and this damage may appear similar to injuries caused by air pollution. A cursory survey of the site in 1997 indicated that several tree diseases and tree-damaging insects were present.

The damage observed on Baseline Mountain could have resulted from one or more of three causes: poor air quality, adverse climate, or naturally occurring pests. To determine the cause, it was necessary to assess the impacts of all natural stresses affecting the ecosystem and to assess sulfur levels in the vegetation as well as in the air. If the observed damage were due to SO_2, it would be expected to be recurrent and easily detectable by instrumentation and by assessment of the vegetation for characteristic symptoms and sulfur (S) concentrations. The recurrent damage would affect tree health and growth in terms of mortality, poor vigor, or dendrochronological (tree ring) effects. In addition, tree health and growth could be expected to differ significantly from the health and growth of trees growing on a site with similar soil, climate, and elevation that was not near a sour gas processing plant and therefore not affected by SO_2 emissions.

This study compared biotic and abiotic characteristics of a forest stand on Baseline Mountain with those of a similar site located in a low SO_2 emission environment on Limestone Mountain. The objectives of this study were as follows: to compare the chemical properties of snow, soil, and foliage, as well as some microclimatic variables, at the Baseline Mountain site with those of control stands on Limestone Mountain, to compare tree health at the Baseline Mountain and Limestone Mountain sites, to examine the condition of cuticular wax on white spruce needles taken from above and below the forest line at both sites, and to examine the tree-ring record for periods of growth loss since the Ram River plant began operations.

METHODS

Site Description

The Baseline Mountain study site was located in a naturally occurring wind-scoured area on the east slope facing the Ram River sour gas processing plant (site elevation: 1796 m) (Fig. 1). This site was selected because, in 1996, foliar damage had been observed on some trees growing near the forest line. The control site was established at a similar wind-scoured area on Limestone Mountain, which is located about 25 km southwest of Baseline Mountain (site elevation: 2002 m). The control site was an area with aspect, elevation, and tree species composition similar to those of the Baseline Mountain site.

Both sites were centered on wind-scoured ridges below the elevational limit of tree growth but with a

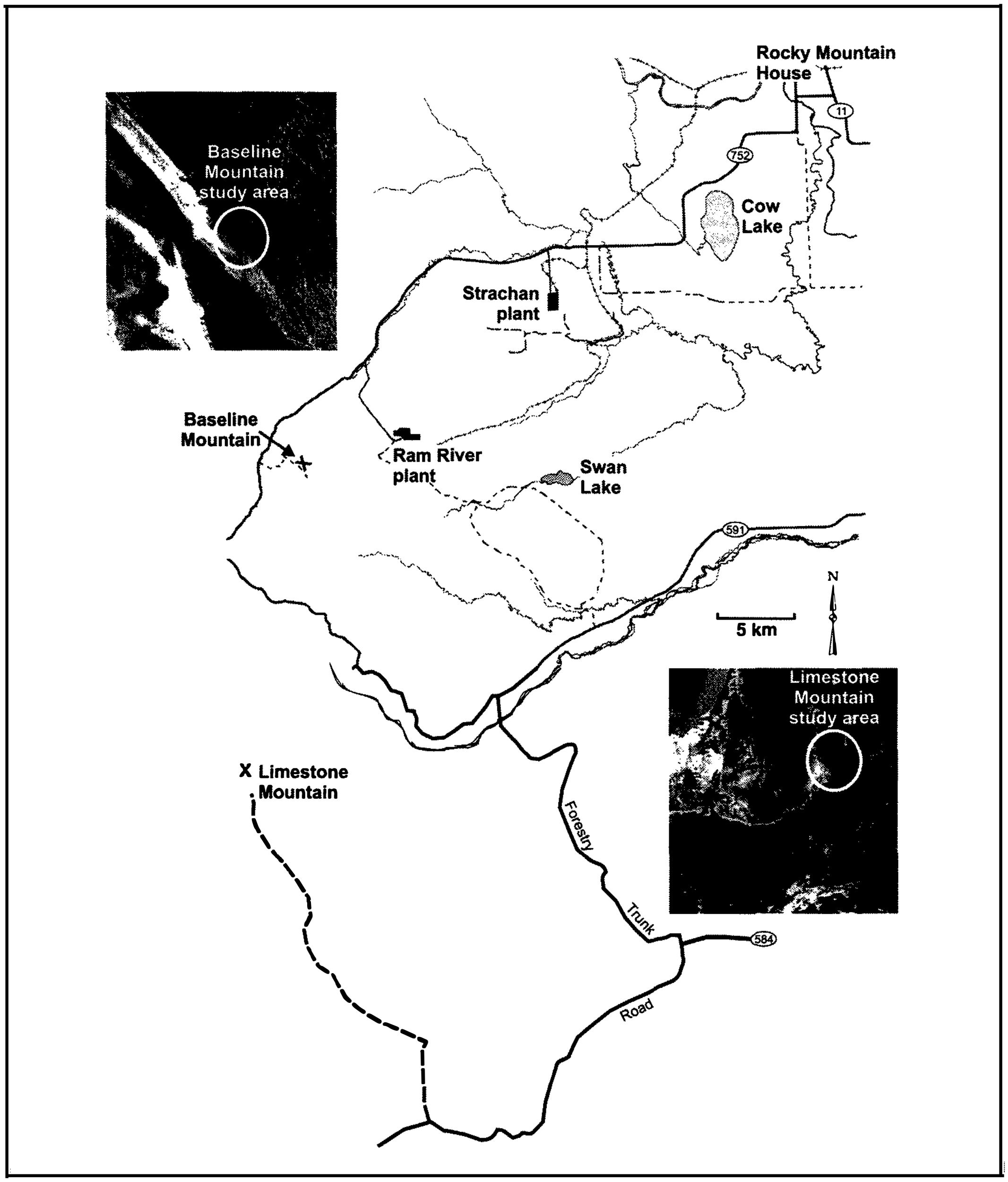

Figure 1. Location of study sites and gas plants. The insets are air photographs of the ridges, with the study sites outlined.

distinct forest line marking the edge of a treeless, wind-scoured meadow. Below the wind-scoured area, the forest stands were composed of lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm.), white spruce (*Picea glauca* [Moench] Voss), and subalpine fir (*Abies lasiocarpa* [Hook.] Nutt.). Some of the spruce near the forest line displayed characteristics of Engelmann spruce (*Picea engelmannii* Parry ex Engelm.). Trees near the wind-scoured area showed stunted and asymmetrical growth similar to that of trees near the elevational limit of tree growth.

Transect Layout

Five replicate transects were established at each site. Each transect measured 2 × 200 m. The transects radiated down the slope, perpendicular to the forest line, from a common center point within the treeless wind-scoured area (Fig. 2). To

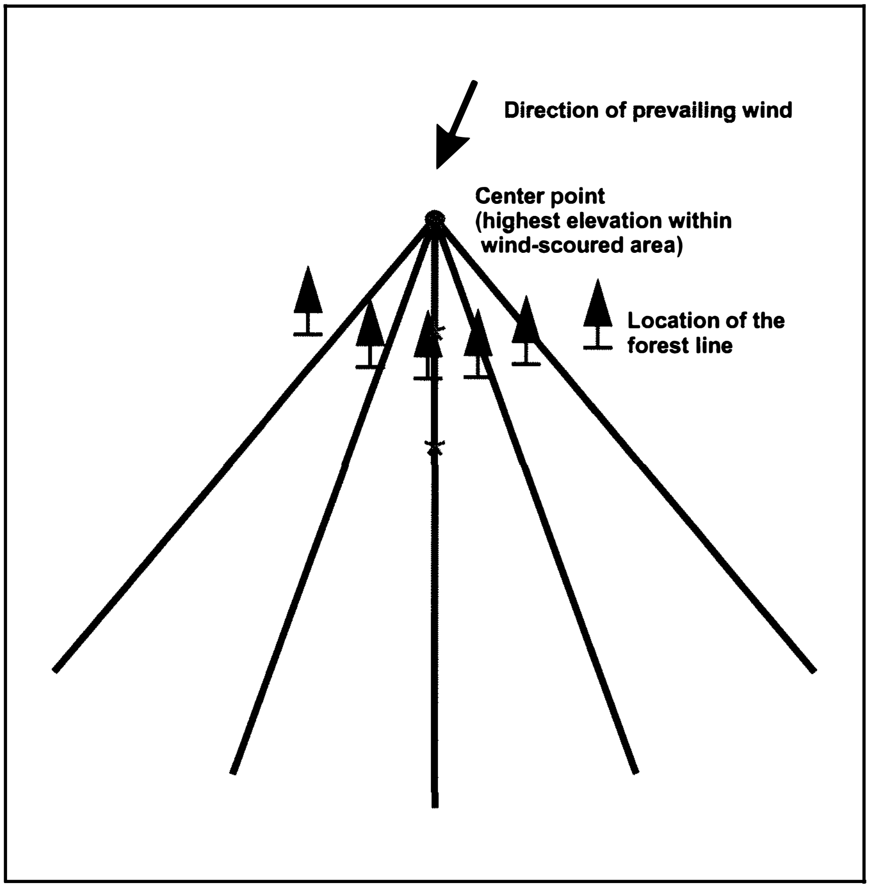

Figure 2. Transect layout for Baseline Mountain and Limestone Mountain study locations. Transects were 2 × 200 m and radiated downhill from a common center point. All trees ≥ 1 cm in diameter at a height of 50 cm were permanently tagged. Tree species were lodgepole pine, white spruce, and subalpine fir. The locations of the microclimate stations are marked by asterisks.

ensure that older, stunted trees at the forest line were included in the analyses, the minimum size for inclusion was 1 cm stem diameter at 50 cm from the soil. Specimens of all three tree species found on the transects and meeting the size criterion, were permanently tagged. Tree height and diameter at breast height (DBH; stem diameter at 1.3 m) were recorded for all tagged trees; for trees with DBH less than 5 cm, the basal diameter was measured.

Climate and Microclimate

The study sites were located within the Subalpine ecoregion, possibly tending toward the Upper Boreal Cordilleran ecoregion at the lowest elevations along the permanent transects (Strong and Leggat 1992). The Subalpine ecoregion in Alberta is characterized by cold, snowy winters and cool, showery summers (Strong and Leggat 1992).

The maximum precipitation falls in July, but winter precipitation is greater in this ecoregion than in any other ecoregion in Alberta (Strong and Leggat 1992). The stress factors associated with climate that most affect vegetation growth are low temperatures, high winds, moisture stress, and a short growing season (Strong and Leggat 1992).

Microclimate was monitored for two winters, from December 1998 to April 1999 and from October 1999 to May 2000. In the 1998/1999 season, three stations were set up, at 0, 25, and 50 m along a 50-m transect running perpendicular to the forest line from the center point within the wind-scoured area into the forest (Fig. 2). Each station was equipped with a Weathermate anemometer to determine wind speeds at a height of 50 cm, a type T copper–constantan thermocouple to assess air temperature at a height of 50 cm, and an acoustic sensor to detect ice particle impacts. At the center point within the wind-scoured area, a wind vane was installed to determine wind direction. A Campbell Scientific 21X data logger was also positioned at the center point, to collect the data from each station on the 50-m transect. Data were recorded at 1-min intervals, and hourly averages were calculated.

The acoustic sensors were built at the Northern Forestry Centre, Edmonton, Alberta, to measure the frequency of impacts from airborne particles carried by winds (P. Hurdle and W. Davis, unpublished design). Each sensor consisted of a piezoelectric acoustic element mounted inside an aluminum cylinder. Wave-sensitive circuitry was calibrated to detect the sound of short, unsustained impacts on the exterior of the aluminum cylinder. The instrument was thus designed to ignore the background sounds of wind and to count only impacts from airborne particles with the potential to damage plant tissues. The count data were compiled by the 21X data logger as number of hits per second. The data obtained from these sensors were used to quantify the potential for mechanical damage to tree parts during the winter.

In the 1999/2000 season the protocol for microclimate monitoring was changed on the basis of results obtained in the first season. New R.M. Young wind monitors were used to reduce the risk of damage from high winds and rime ice in the center of wind scoured plots. Rime ice forms when water droplets in the air collide with supercooled objects and subsequently freeze (Perla and Martinelli 1975). The stations at 25 and 50 m from the center point were removed, and the acoustic sensors from those stations were installed at the forest line. The station in the center of the wind-scoured area logged wind speed and direction at 150 cm above the snow level. Air temperature and ice impacts were measured at 10 to 50 cm above the snow level. Temperature, wind speed, and ice impacts were logged at 1-min intervals and averaged hourly. Wind direction was output as a histogram of the mean direction weighted by wind speed in eight 45° sectors at 0500 and 1700 (mountain standard time).

For each season the hourly records were combined as a set of summary line graphs to allow visual comparison of the Baseline Mountain and Limestone Mountain sites. Monthly and seasonal maximum, minimum, and mean values were calculated for each operating sensor. The number of freeze–thaw cycles for each winter measurement season was calculated and compared with data for a low-altitude site at the airport in Rocky Mountain House, Alberta. For the 1999/2000 season the monthly wind direction was summarized in histograms weighted by wind speed.

Snow Sampling

In the 1998/1999 season, snow course measurements were made at 1-month intervals in March and April 1999, and snow samples were collected for chemical analysis at those times. A snow pit was dug in an area of undisturbed snowpack next to each microclimate measurement station along the 50-m transect perpendicular to the forest line. The snow pits represented snowpack characteristics in the wind-scoured area, the drift area at the forest line, and the sheltered, closed-canopy area. Crystal type and size, layer depth, and snow density were described for each layer within the snowpack (Perla and Martinelli 1975). Snow density was calculated using the weight of a known volume of snow obtained with a rectangular scoop of 100 cm^3 volume. For analysis of total S by inductively coupled plasma–atomic emission spectroscopy (ICP–AES) (Kalra and Maynard 1991), a sample of snow was collected from each layer with a plastic scoop and kept frozen in a plastic bag for transport and storage. Samples were melted at room temperature, filtered, and acidified before ICP–AES.

In the 1999/2000 season, snow was sampled twice, in January and March 2000. The sampling methods were changed on the basis of results of statistical analysis of the 1998/1999 data. Those data showed that there were no significant differences along the transects or between layers within each site; therefore, just one pit was dug for snow description, as above. The snow samples were obtained with a plastic tube of known diameter. The tube was inserted into the snowpack at right angles to the ground surface, and the entire column of snow inside the plastic tube was returned to the laboratory in a plastic bag, where it was kept frozen in a cooler. Total S was analyzed by ICP–AES as in the previous year. Raw data for the description of snow pits are not reported here but are archived at the Northern Forestry Centre.

Soil and Foliar Analysis

Five samples of each of the forest floor horizons (LFH material, an organic layer developed primarily from leaves, twigs, and woody matter) and the upper 10 cm of mineral soil horizons were obtained along each transect in October 1998. There was no soil at the beginning of each transect. Consequently, the first samples were taken 20 m from the beginning of the transect. The four subsequent soil samples were taken at 40-m intervals from the first sampling location. Samples were double bagged and stored at −3°C until analysis. Chemical analysis of soil and forest floor samples were completed during the following winter.

Chemical analyses of forest floor samples were done according to Kalra and Maynard (1991): pH in 0.01 M $CaCl_2$, extractable S by NH_4Cl extraction and ICP–AES, total S by microwave digestion and ICP–AES, cation exchange capacity (CEC) and exchangeable cations with 1 M NH_4Cl and ICP–AES for cations, total Kjeldahl N by block digestion and Tecator Auto 1030 analyzer distillation, and extractable P by Bray P extraction and ICP–AES. Total C was determined with a LECO CR-12 carbon furnace (Nelson and Sommer 1982).

Mineral soil was analyzed according to the same methods used for forest-floor samples, except for extractable S, which was determined by $CaPO_4$ extraction and ICP–AES (Kalra and Maynard 1991); total S was not determined for mineral soil.

Foliage samples were taken from five trees of each species on each transect near the soil sampling locations in early November 1999. Current-year foliage was sampled from one-third to one-half of the distance from the top to the bottom of the live crown. Samples were oven-dried for 24 h at 70°C directly upon return to the laboratory and were ground before analysis. Foliage was analyzed according to Kalra and Maynard (1991). Total S, total P, and macronutrient and micronutrient cations were determined by microwave digestion and ICP–AES. Foliar sulfate S (SO_4-S) was determined by extraction in HCl and ICP–AES. Foliar N was determined as total Kjeldahl N. Passive SO_2 stations (Maxxam exposure cylinders) were placed at the Baseline Mountain and Limestone Mountain sites to measure the average concentration of SO_2 in the air over periods of about 6 months and were monitored by Husky Oil Operations Limited.

Tree Health Survey

The health of all permanently tagged trees on Baseline and Limestone mountains was surveyed in June 1999. Each tree along the transects was assessed individually for health and was classified as either healthy, declining, recently dead, or dead more than 1 year. Damage to tree parts and the agent responsible for the symptom or sign were recorded for each tree. Methods for classifying health and recording symptoms and disease or insect diagnosis were as described by Maynard et al. (1994). In addition, the crown form of the tree was determined according to the Griggs–Putnam index of wind deformation (Putnam 1948; Wade and Hewson 1979) (Fig. 3) to document the mechanical deformation by wind of trees at the forest line. Each tree was subjectively classified on a scale from 1 to 8 (Fig. 3). Examples of actual trees at Baseline Mountain and their crown-form class are shown in Figure 4.

Epicuticular Wax Studies

Epicuticular waxes are produced on the surface of conifer needles as protection against damaging agents in the environment. Epicuticular wax is a fine aggregate of tubular crystallites occurring at various densities across the leaf surface. The structure may be damaged or altered by weather events. It has been shown that, for east coast balsam fir (*Abies balsamifera* [L.] P. Mill), the amount of epicuticular wax increases with elevation and that the fine structures of the wax layer are less evident on trees at high altitudes (DeLucia and Berlyn 1984).

In 1998/1999, a wax candle method (Hadley and Smith 1989) was used in an attempt to calibrate the data obtained from the acoustic sensors concerning potential damage to the layer of epicuticular wax on conifer needles. Winter injury is thought to be caused by desiccation of needles that have been damaged by abrasion of the protective surface wax. The wax candles were made from a 1:1 mixture of paraffin and carnauba wax and were mounted on the microclimate masts at the same level as the acoustic sensors. The density of the wax mixture was 0.846 g/cm^3, as measured by displacement, comparable to the known density of *P. engelmannii* epicuticular wax (0.90 g/cm^3) (Hadley and Smith 1989). The candles were coated with a thin layer of colored paint and weighed before installation in the field. It was assumed that if the paint was abraded or a measurable amount of wax was lost from the candle, mechanical injury could be inferred. The candles were replaced each time the stations were visited during the winter (approximately once each month from installation until snowmelt).

In 1999/2000 the wax candle trial was discontinued, and an experiment with white spruce trees, both planted deliberately and occurring naturally,

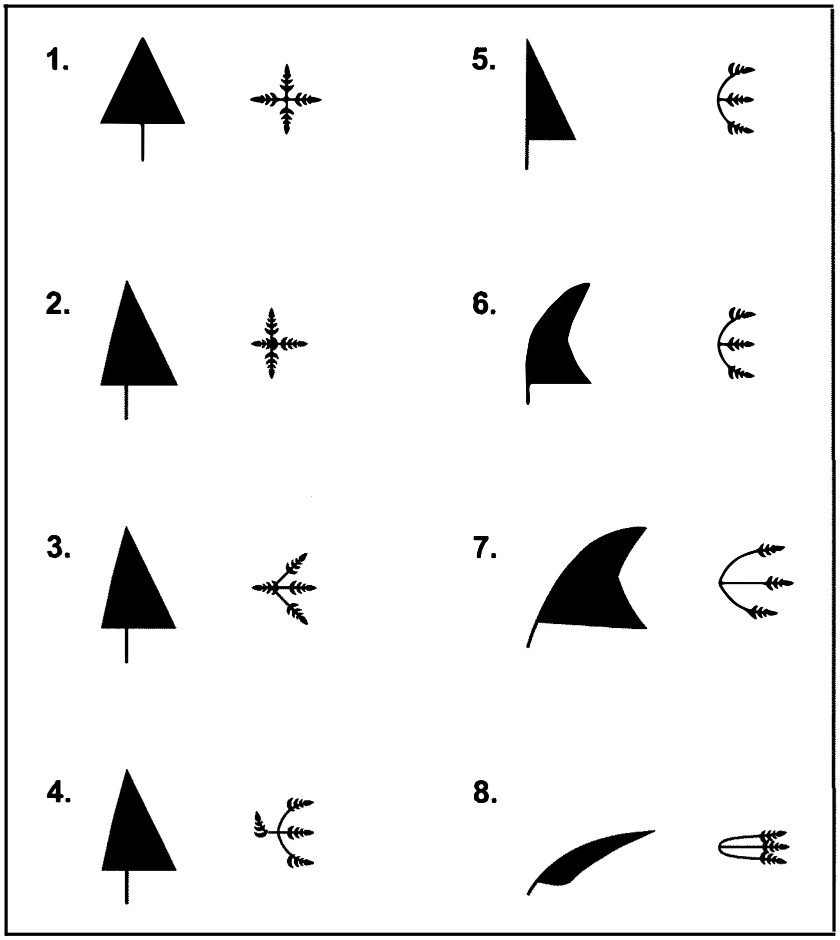

Figure 3. Crown-form classification codes used in the tree health survey for assessing mechanical damage to trees. Each tree was rated as to the extent of stem and branch damage due to wind and particle erosion. For each number in this schematic, a lateral and overhead view of the tree is shown. The classification system is taken from Putnam 1948.

was initiated to measure the loss of epicuticular wax over a winter measurement season.

White spruce seedlings (Jasper provenance) were planted above and below the forest line at the Baseline Mountain and Limestone Mountain sites in spring 1999, just before bud break. At each site, twenty seedlings were planted above the forest line and 20 seedlings below the forest line, in a sheltered area. The shoots were allowed to elongate over the summer, and in November 1999, new shoots were sampled for analysis (see below). The seedlings were left for the winter months, and in spring 2000, the 1999 shoots were resampled. In addition, a total of 10 naturally occurring white spruce from above and 10 from below the forest line were selected and sampled at the same time as the planted seedlings. The analysis encompassed the four sets of trees at each site and a control set of trees in Edmonton, for a total of 9 sets of planted or naturally occurring trees. The sets of trees were coded as to location, origin, and position, where location was Baseline (B) or Limestone (L), origin was planted (P) or natural (N), and position was upper (U) or lower (L). For example, a tree coded as BPU (Baseline planted upper) was a seedling planted above the forest line at the Baseline Mountain site.

At each sampling time, two shoots were taken from each seedling and each naturally occurring tree.

White spruce (2) White spruce (3) White spruce (4)

Lodgepole pine (5) White spruce (5) Lodgepole pine (5)

Figure 4. **Some examples of alterations to normal symmetrical crown form caused by wind and other environmental factors at Baseline Mountain.** The numbers correspond to the Griggs–Putnam index values (Putnam 1948) that were assigned to the trees on the basis of the extent of mechanical damage.

Each shoot was placed in a 25-mL scintillation vial for return to the laboratory. The epicuticular wax was extracted by washing the needles in 5 mL chloroform for 10 s. The needles were removed from the filtrate using a Buchner funnel, and the scintillation vial was rinsed once with 5 mL chloroform. The rinse was added to the filtrate through the Buchner funnel, and the entire chloroform extract was left to evaporate under a fume hood in a preweighed aluminum tray. Once the chloroform had evaporated, the tray was weighed. The needles were dried at 70°C for 24 h and weighed. Amount of wax was expressed as weight of dry wax in relation to weight of dry needles.

A few needles from each of the four sets of trees at each site and from the control site in Edmonton were reserved for scanning electron microscopy.

Each needle was mounted on a stub, sputter coated with gold, and photographed with a Jeol 6301FXV scanning electron microscope. Photographs were taken at 5 kV at a stage temperature of –150°C. Two samples were randomly chosen from each of the four sets at each location and from the control site in Edmonton, for a total of 18 needles. The surface features were examined at mid-needle and at the needle tip. Surface features included stomata, areas immediately adjacent to stomata, and ridges or raised areas. Representative features of each needle section were identified and photographed. Trees were sampled in August and September.

Stem Analysis

Twenty-five codominant trees at each site were selected for stem analysis. These trees were taken from areas between the permanent transects. The trees selected for stem analysis represented the dominant species in each stand along the elevational gradient represented by the five transects. The height and DBH of felled trees were measured, and each stem was divided into 20 equal sections. A disk 5 cm thick was removed from the middle of each section; the first being the basal disk (disk from the stem section closest to ground level). Disks were labeled as to tree number, disk number, and windward side and were stored at –3°C.

Before the disks were prepared for X-ray densitometry, the mean wet radius, maximum and minimum wet radii, windward and leeward wet radii, and wet diameter were measured. Wedge cutting, extraction, and photography for X-ray densitometry were done according to the method of Varem-Sanders and Campbell (1996).

A separate stem analysis was undertaken over the period 1998–2000. In 1998, four lodgepole pines at the Baseline Mountain site and eight lodgepole pines at the Limestone Mountain site were cut and sampled. In 1999, 12 more lodgepole pines were cut and sampled at each site to explore the hypothesis, arising from analysis of the 1998 samples, that red belt was the cause of significant growth losses. The trees cut in 1999 were taken from similar elevations as and were of similar age to those cut in 1998. In addition, two new sample sites were established on the west-facing slopes of Baseline and Limestone mountains, and 12 lodgepole pines were cut and disks sampled from each of these locations. Thus, for the 1999 analysis there were four different sites: Baseline east (same as in 1998), Limestone east (same as in 1998), Baseline west (new in 1999), and Limestone west (new in 1999). The 1999 analysis consisted of 48 trees. Disks were cut from all the newly felled trees at 1-m intervals beginning with the basal disk. All disks were labeled with the tree and disk numbers and were stored at –3°C until preparation for X-ray densitometry, as described above.

Once the ring-width chronologies had been cross-dated by means of DendroScan software (Varem-Sanders and Campbell 1996), various indices of tree growth were calculated and plotted. Curves were obtained for annual height, oblique sequences, annual volume, cumulative volume, and specific volume increment. These calculations were performed with the computer program Analysis of Disks, as described in Maynard et al. (1994).

Tree growth was analyzed on the basis of specific volume increment, which is known to be the most sensitive measurement of air pollution (Maynard et al. 1994). The trees were grouped into species and age-class categories before comparison between Baseline and Limestone mountains. The average specific volume increment at Limestone Mountain for the 10-yr period prior to 1972 (beginning of plant operations) (G_{Lp}) was assumed to represent the growth of trees near the forest line in an environment subject to low SO_2 emissions. Similarly, the average specific volume increment at Baseline Mountain for the 10-yr period prior to 1972 (G_{Bp}) was assumed to represent the growth of trees without any SO_2 effects. The ratio of growth before 1972 between trees at the two sites was then calculated and multiplied by the average growth at Limestone Mountain after 1972 (G_{La}) to obtain an estimate of growth at Baseline Mountain (G_{Be}) if the Ram River plant had not been constructed:

$$G_{Be} = G_{La} \times (G_{Bp} / G_{Lp}) \tag{1}$$

Finally, growth loss (positive value) or gain (negative value) (L_B)was calculated by comparing the estimated growth curve to the measured growth curve at Baseline Mountain:

$$L_B = (G_{Be} - G_{Ba}) / G_{Be} \tag{2}$$

where G_{Ba} is the average specific growth at Baseline Mountain after 1972. Regression analysis was performed for each specific volume increment record for each tree to show only the growth curve affected by extrinsic factors. Fritts (1976) described the natural growth of North American conifers as an exponential decay equation:

$$y_x = ae^{-bx} + c \qquad (3)$$

For each tree, the best-fit exponential decay equation was calculated, and the residuals were graphed in a time series. Departures from zero values on these charts should represent positive and negative effects on tree growth caused by environmental factors. The mean residuals for each group of trees were calculated for each year, and a graph was produced for each of the four sites in the 1999/2000 analysis.

The same calculations of growth indexes and growth loss were performed for the 1999 samples taken to test the red belt hypothesis (four groups of 12 trees). Values were calculated for the 10-yr period after 1968 because that is the suspected date of red belt occurrence on Baseline Mountain. Growth losses were calculated for 1) Baseline Mountain east site, with Limestone Mountain east site as a control, 2) Baseline Mountain east site, with Baseline Mountain west site as a control, 3) Baseline Mountain west site with Limestone Mountain west site as a control, and 4) Limestone Mountain east site, with Limestone Mountain west site as a control.

RESULTS AND DISCUSSION

Stand Structure

Lodgepole pine, white spruce, and subalpine fir were present on both Baseline and Limestone mountains in different proportions. A total of 1258 trees of all three species were tagged and measured (702 trees at the Baseline Mountain site and 556 trees at the Limestone Mountain site). At the Limestone Mountain site, lodgepole pine was the most numerous species, accounting for 66.4% of tagged trees. At the Baseline Mountain site, the population of lodgepole pine (20.4%) was similar to that of white spruce (26.4%) (Table 1).

At the Baseline Mountain site, the average DBH for trees ≥ 50 mm DBH was 118 mm for white spruce and 124 mm for pine. The average height was 7.6 m for spruce and 8.4 m for pine (Table 2). Thus, even though there were similar numbers of pine and spruce at the Baseline Mountain site, the pine usually overtopped the spruce and dominated the canopy. There were four times as many fir at the Baseline Mountain site as there were at the Limestone Mountain site; however, most of these trees were located in a band across the hillside, 50 to 75 m from the start of the transects. Of these trees, 74% were less than 50 mm DBH and thus represented an understory species. In summary, both sites may be described as lodgepole pine dominated sites with a spruce–fir understory, but white spruce and subalpine fir were more common at the Baseline Mountain site than at the Limestone Mountain site.

Stand age was determined from the disks used in the stem analysis. The maximum age of lodgepole pine was 118 yr for Baseline Mountain and 72 yr for Limestone Mountain. Most of the pines at the Baseline Mountain site were 70–89 yr of age, wheras those at the Limestone Mountain site were 40–69 yr of age (Fig. 5). The maximum age of white spruce and subalpine fir was 103 and 142 yr, respectively,

Table 1. Species composition for transects at Baseline Mountain and Limestone Mountain sites

	Baseline Mountain			Limestone Mountain		
Species	No. of trees	% of total	% of total ≥ 50 mm DBH	No. of trees	% of total	% of total ≥ 50 mm DBH
Lodgepole pine	143	20.4	16.7	369	66.4	57.0
White spruce	185	26.4	18.5	95	17.1	8.2
Subalpine fir	374	53.3	19.2	92	16.5	7.2
Total	702			556		

Note: DBH = diameter at breast height.

Table 2. **Mean height and mean DBH of all tagged trees ≥ 50 mm DBH**

	Baseline Mountain		Limestone Mountain	
Species	Mean height (m)	Mean DBH (mm)	Mean height (m)	Mean DBH (mm)
Lodgepole pine	8.4	124	8.8	125
White spruce	7.6	118	3.9	68
Subalpine fir	6.4	77	4.8	89

Note: DBH = diameter at breast height.

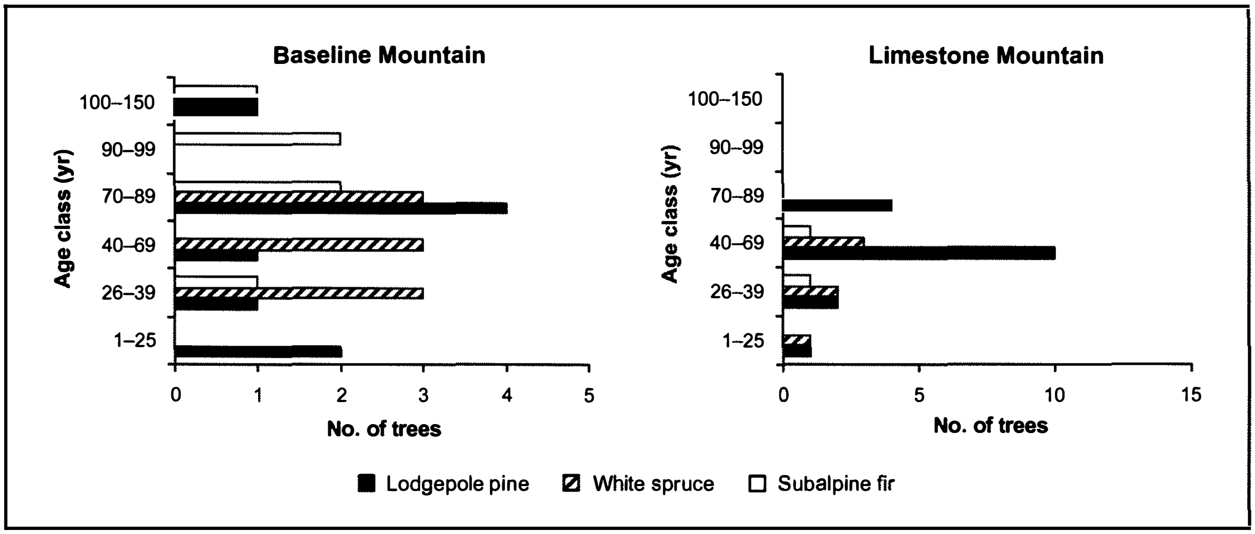

Figure 5. Age distribution of trees used for stem analyses.

Table 3. **Average SO_2 concentrations of air**

Period	Average SO_2 concentration (ppb)[a]	
	Baseline Mountain	Limestone Mountain
November 1998 to May 1999	1.3a	1.1a
May 1999 to December 1999	1.6a	0.9b
December 1999 to May 2000	1.3a	0.7b

[a] Sites were compared for each period by means of the Student *t*-test. Values for the same period followed by different lowercase letters were significantly different ($P = 0.05$).

at the Baseline Mountain site and 49 and 53 yrs, respectively, at the Limestone Mountain site. Fire scars were observed on Limestone Mountain but not Baseline Mountain; thus, the more recent occurrence of fire on Limestone Mountain could account for the difference in stand age. The Limestone Mountain stand was at an earlier successional stage than the Baseline Mountain stand, which accounts for the differences in species composition.

Ambient SO_2 Concentrations

Passive SO_2 stations (Maxxam exposure cylinders) were placed at the Baseline Mountain and Limestone Mountain sites to measure the average concentration of SO_2 in the air over periods of about 6 months and were monitored by Husky Oil Operations Limited. A Student *t*-test was performed on the values obtained for three measurement periods during the course of the 2-yr study (Table 3). There was no significant difference in the SO_2 concentrations for the period November 1998 to May 1999, but there were significant differences ($P = 0.05$) for the other two periods. For comparison, the average SO_2 concentration for the Parkland Airshed Management Zone in 1999–2000 was 1.26 ppb (range 0.1–2.2 ppb) (David McCoy, Husky Oil Operations Limited, Calgary, Alberta, conversation, and data December 2000). All values were well below the federally defined maximum desirable level of 10 ppb (Alberta Energy Resources Conservation Board 1989).

Snow

Snow course measurements were made for two periods in each of 1998/1999 and 1999/2000 to determine total S deposition. Samples were taken from snow layers, which represented either snowfall or redistribution events, in pits at each site. Two-way analysis of variance for the 1998/1999 data indicated no significant differences between the two sites for either of the sampling periods (Table 4).

However, in 1999/2000, there was a significant difference between the sites in total S concentration in melted snow for both measurement periods (Table 4). The values for the Baseline Mountain site were three to nine times greater than those for the Limestone Mountain site. Comparison with the values obtained in 1998/1999 showed that the S concentration at the Limestone Mountain site had decreased, while the S concentration at the Baseline Mountain site had remained constant. These snow chemistry results support the results obtained for SO_2 concentrations in air.

Soils and Foliage

Soil profile descriptions, chemical data, and soil classifications are shown in Appendix 1. Soil and foliar chemical properties at the Baseline Mountain and Limestone Mountain sites were compared to determine if there were measurable differences in chemical properties between the two locations. Differences in soil and foliar S status between the sites could indicate significantly different levels of atmospheric S inputs. Soil and foliar chemistry for the two study sites were also compared with soil and foliar chemistry for a site close to Baseline Mountain that had been characterized in a previous study on S impacts (Maynard et al. 1995: site 24,

Table 4. Mean total S in melted snow samples for two periods in each of 1998/1999 and 1999/2000

Date	Mean S content of snowpack (mg/L in water)[a]	
	Baseline Mountain	Limestone Mountain
1998/1999		
March 1999	0.29a	0.21a
April 1999	0.27a	0.22a
1999/2000		
January 2000	0.29a	0.09b
March 2000	0.27a	0.03b

[a] Data for each winter were tested separately by two-way analysis of variance and least-squared mean multiple-comparison test, with location and sampling period as the parameters. Values for the same winter followed by different lowercase letters were significantly different ($P = 0.05$).

1991 measurements). In that study, site 24 was characterized as "medium" with respect to S deposition and total forest-floor S concentration.

There were no differences in extractable S concentration between the two sites for either forest floor or surface mineral soil (Tables 5 and 6). Extractable S represents what is available to plants or can be readily made available through microbial processes. These fractions would have the greatest impact on plant S status and nutritional balances. Extractable S concentrations for forest floor samples were considerably lower on both Baseline Mountain and Limestone Mountain than at site 24 (Table 5). This suggests that the rates of active S cycling in the forest floor at these sites were lower than at site 24, which is consistent with lower S inputs. Extractable S values for mineral soil were comparable at the three locations, which reflects lack of S accumulation at the Baseline Mountain site relative to Limestone Mountain and to site 24 since 1991.

Total S concentration in forest floor samples from Baseline Mountain was the same as that observed at site 24 in 1991 (0.14%), which indicates that S had not been accumulating at Baseline Mountain relative to site 24 since 1991. Total S concentrations in forest floor samples were significantly greater for Baseline Mountain (0.14%) than for Limestone Mountain (0.12%); however, both values were at the low end of the range of total S concentration in forest floor material reported previously (0.10 to 0.20%) (Kishchuk 1998).

Soil acidification could be expected under conditions of substantial atmospheric S deposition. However, soil pH was significantly greater in both forest floor and mineral soil on Baseline Mountain than on Limestone Mountain (Tables 5 and 6). Surface mineral soil pH was nearly 6 on Baseline Mountain, and the soil was somewhat calcareous, as indicated by field effervescence tests. The soil acidity findings were supported by high concentrations of exchangeable Ca and Mg in Baseline Mountain samples (Table 5).

The concentrations of Ca and Mg were substantially greater on Baseline Mountain than on Limestone Mountain or at site 24 (Tables 5 and 6). The mean soil pH value of 5.8, the presence of carbonates, high concentrations of exchangeable Ca and Mg, and the high CEC of the surface soils on Baseline Mountain indicate that they were base saturated and well buffered and would not readily be acidified. Percent base saturation could not be determined for Baseline Mountain soils, as the sum of exchangeable base cations exceeded the measured CEC. An alternative method of determining CEC and exchangeable cations might have been more appropriate for soils such as these, in which carbonates are present (Kalra and Maynard 1991). The high Mg concentrations are indicative of dolomitic limestones in the soil parent material.

The soil on Limestone Mountain was more acidic than the soil on Baseline Mountain and was within the pH range where exchangeable aluminum (Al), iron (Fe), and manganese (Mn) may constitute a significant proportion of the exchange complex. This hypothesis is supported by the finding that base cations did not fully account for the CEC in the Limestone Mountain soils. Exchangeable Al, Fe, and Mn were not determined for the soil samples from the transects; however, chemical analyses of mineral soil samples from the soil profiles indicate that Al and Fe constituted a significant proportion of the exchange complex in these soils (Appendix 1).

Total S, sulfate-S (SO_4-S), and other nutrient concentrations in lodgepole pine, white spruce, and subalpine fir foliage were compared between the Baseline Mountain and Limestone Mountain sites. Lodgepole pine and white spruce foliar nutrient concentrations for these two sites were also compared with data from site 24 (Maynard et al. 1995). As with soils, significant atmospheric S inputs should be reflected in foliar S and SO_4-S concentrations. Sulfur in excess of that required for immediate use in protein formation accumulates as SO_4-S, rendering concentrations of SO_4-S a good indicator of plant S status. Concentration of S and other nutrients are shown in Table 7.

The only difference in foliar S and SO_4-S concentrations between the Baseline Mountain and Limestone Mountain sites was observed in lodgepole pine for which total S concentrations were slightly but significantly higher on Limestone Mountain (0.10%) than on Baseline Mountain (0.09%). Foliar S concentrations in lodgepole pine and white spruce from Baseline Mountain were comparable to or lower than values observed at site 24 in 1991, indicating an absence of S accumulation at the Baseline Mountain site beyond what was observed in 1991. Sulfur concentrations in foliage from Baseline Mountain and Limestone Mountain were low relative to values reported in the literature, even for sites with very low S deposition (Kishchuk 1998). Foliar S concentrations at the study sites (0.08 to

Table 5. Chemical composition of forest floor (LFH material)[a]

Parameter	Baseline Mountain ($n = 21$)	Limestone Mountain ($n = 17$)	Site 24[b]
pH ($CaCl_2$)	4.7a	3.9b	4.4 ± 0.3
Extractable S (mg kg^{-1})	44	47	151 ± 42
Total S (%)	0.14a	0.12b	0.14 ± 0.02
Exchangeable Ca (cmol kg^{-1})	46.7a	22.1b	15.8 ± 1.7
Exchangeable Mg (cmol kg^{-1})	11.9a	5.8b	3.7 ± 0.7
Exchangeable K (cmol kg^{-1})	1.7	1.9	2.7 ± 1.1
Exchangeable Na (cmol kg^{-1})	0.2	0.2	ND
Cation exchange capacity (cmol kg^{-1})	71.7a	43.1b	ND
Base saturation (%)	85a	69b	ND
Total N (%)	1.44a	1.25b	1.27 ± 0.11
Extractable P (mg kg^{-1})	56	106	239 ± 119
Carbon (%)	44.4	43	ND

[a] Values for the same constituent followed by different lowercase letters were significantly different at the Baseline Mountain and Limestone Mountain sites ($P = 0.05$). Site 24 data were not used in the analysis and are presented for comparative purposes only.

[b] Maynard et al. (1995). Data presented as mean ± 95% confidence limits.

Note: LFH = forest floor, ND = not determined.

Table 6. Chemical composition of mineral soil (0–10 cm)[a]

Parameter	Baseline Mountain ($n = 25$)	Limestone Mountain ($n = 25$)	Site 24[b]
pH ($CaCl_2$)	5.8a	3.6b	4.8 ± 0.4
Extractable S (mg kg^{-1})	31	30	38 ± 47
Exchangeable Ca (cmol kg^{-1})	24.7a	5.3b	2.3 ± 1.3
Exchangeable Mg (cmol kg^{-1})	11.6a	1.3b	0.7 ± 0.5
Exchangeable K (cmol kg^{-1})	0.4	0.2	0.3 ± 0.1
Exchangeable Na (cmol kg^{-1})	0.1	0.1	ND
Cation exchange capacity (cmol kg^{-1})	31.5a	17.6b	ND
Base saturation (%)	NA	39	ND
Total N (%)	0.23a	0.19b	ND
Extractable P (mg kg^{-1})	5a	21b	ND
Carbon (%)	5.0	4.3	ND

[a] Values are means of first two mineral horizons (0–14 cm). Values for the same constituent followed by different lowercase letters were significantly different at the Baseline Mountain and Limestone Mountain sites ($P = 0.05$). Site 24 data were not used in the analysis and are presented for comparative purposes only.

[b] Maynard et al. (1995). Data presented as mean ± 95% confidence limits.

Note: NA = not applicable (base saturation values could not be determined because of high Ca concentrations), ND = not determined.

Table 7. Current-year foliar nutrient concentrations (1999)

Nutrient	Baseline Mountain (n = 25)	Limestone Mountain (n = 25)	Site 24
Subalpine fir			
S (%)	0.09	0.10	ND
SO_4-S (mg kg^{-1})	188	236	ND
N (%)	1.18	1.10	ND
P (%)	0.15a	0.21b	ND
Ca (%)	0.41a	0.32b	ND
Mg (%)	0.11a	0.08b	ND
K (%)	0.70	0.60	ND
Fe (mg kg^{-1})	22a	42b	ND
Mn (mg kg^{-1})	452a	894b	ND
Lodgepole pine			
S (%)	0.09a	0.10b	0.10 ± 0.01
SO_4-S (mg kg^{-1})	286	336	ND
N (%)	1.03	1.06	1.10 ± 0.06
P (%)	0.12	0.14	0.15 ± 0.02
Ca (%)	0.19	0.15	0.16 ± 0.02
Mg (%)	0.12a	0.08b	0.09 ± 0.01
K (%)	0.48a	0.41b	0.60 ± 0.04
Fe (mg kg^{-1})	28b	43a	27 ± 3
Mn (mg kg^{-1})	184b	384a	322 ± 54
White spruce			
S (%)	0.08	0.08	0.10 ± 0.004
SO_4-S (mg kg^{-1})	192	176	ND
N (%)	0.98	0.93	1.08 ± 0.04
P (%)	0.14a	0.18b	0.23 ± 0.02
Ca (%)	0.43a	0.29b	0.38 ± 0.08
Mg (%)	0.10a	0.07b	0.12 ± 0.01
K (%)	0.62	0.57	0.75 ± 0.07
Fe (mg kg^{-1})	24a	35b	23 ± 11
Mn (mg kg^{-1})	238a	423b	501 ± 271

[a] Values for the same constituent followed by different lowercase letters were significantly different ($P = 0.05$). Site 24 data were not used in the analysis and are presented for comparative purposes only.

[b] Maynard et al. (1995). Mean ± 95% confidence limits.

Note: ND = not determined.

Table 8. Minimum air temperature 50 cm above snow level and maximum particle impact frequency (December 1998 to March 1999)

Site	Minimum temperature (°C)		Maximum particle impact frequency (× 10^{-2} hits/s)	
	Baseline Mountain	Limestone Mountain	Baseline Mountain	Limestone Mountain
Exposed	–28.9	–29.4	13.35	166.8
Forest line	–29.2	–29.6	0.01	4.131
Sheltered forest	–29.4	–30.5	0.489	5.894

0.10%) are in fact indicative of S deficiencies in conifers (Ballard and Carter 1985). Sulfate-S concentrations in foliage in this study ranged from about 175 to about 335 mg kg^{-1}. These values fall in the low to mid-range reported in the literature. Sulfate-S concentrations of nearly 900 mg kg^{-1} have been observed in lodgepole pine foliage near an S processing plant near Whitecourt, Alberta (Legge, Bogner et al. 1988). Low to moderate foliar S status, minimal differences in foliar S and SO_4-S concentration between locations, and lower or comparable foliar S at the Baseline Mountain site relative to the "medium" deposition site 24 all indicate an absence of significant S accumulation at the Baseline Mountain site.

Foliar N concentrations indicate moderate to severe N deficiencies for all species, particularly white spruce (Ballard and Carter 1985). Lower foliar concentrations of P, Fe, and Mn, and higher foliar concentrations of Ca and Mg for Baseline Mountain than for Limestone Mountain likely reflect differences in nutrient availability, related to the calcareous soil conditions on Baseline Mountain (Kishchuk 2000).

Soil and foliar nutrient analyses indicated very little difference in S levels between the Baseline Mountain and Limestone Mountain sites. In addition, the S status of soil and foliage at the Baseline Mountain site was comparable to or lower than that determined at the nearby site 24 in 1991 (Maynard et al. 1995). Soil and foliar S levels observed at site 24 were not associated with adverse effects on forest productivity or health (Maynard et al. 1994), and given that the S concentrations for Baseline Mountain were similar or lower, no such effects can be expected to be occurring on Baseline Mountain.

Winter Microclimate

For the 1998/1999 season, full records were obtained for frequency of ice particle impact and air temperature at both locations (Fig. 6). Partial records for wind speed were obtained from both sites but were not used in the interpretation because the occurrence of rime ice at both locations was enough to prevent the anemometer cups from turning freely at all times. In this case, the metal components of the anemometers became cold enough during the winter for rime ice to form during high winds; rime ice was observed on three occasions during the monthly station maintenance checks between December 1998 and April 1999.

The acoustic sensors were built to quantify the potential for cuticular wax erosion, which is a wind-driven effect whereby the surface wax of individual needles is eroded by wind-borne snow particles (Hadley and Smith 1989). The needles and branches closest to the snow surface, where the potential for erosion is greatest, are damaged, as are needles and branches facing into the prevailing wind (Holtmeier 1980; Hadley and Smith 1989).

The data on ice particle impact and temperature were highly correlated between the Baseline Mountain and Limestone Mountain sites; the r^2 value for hourly temperature records was 0.970 ($P = 0.001$). At least one winter storm affected the two sites simultaneously during the period 18 to 21 December 1998; maximum particle impacts and minimum temperatures were measured during this period (Table 8). Even though the particle impact and temperature data at the two sites were highly correlated, there were differences in the frequencies of particle impacts. Maximum values on Limestone Mountain were higher than those on Baseline Mountain for all sites along the vegetation gradient from exposed to sheltered forest. In addition, the acoustic sensors clearly demonstrated the rapid decline in frequency of particle impacts from the exposed site across the forest line into the closed forest stand (Table 8).

The wax candles used to link the particle impact frequency data with potential for damage to tree tissues were not eroded enough to obtain a measurable weight loss over the exposure period. The only time the thin paint coating on the candle exterior was eroded was in December 1998 and January 1999, when the maximum particle impacts were recorded. Thus, the maximum values for Baseline and Limestone mountains obtained during the winter storm may represent a threshold value for particle impact frequency up to which a tree can maintain its layer of epicuticular wax. More testing would be required to calibrate the measurements taken from the acoustic sensors with actual erosion of the epicuticular wax.

With improved wind-monitoring equipment, full records for wind speed and mean wind direction weighted by wind speed were obtained for the period October 1999 to May 2000 (Figs. 7–9). Four of the six acoustic sensors produced reliable results (Figs. 10 and 11). The two sensors that failed were located at the forest line on Baseline Mountain (Fig. 10). The data gap occurred between 1 January

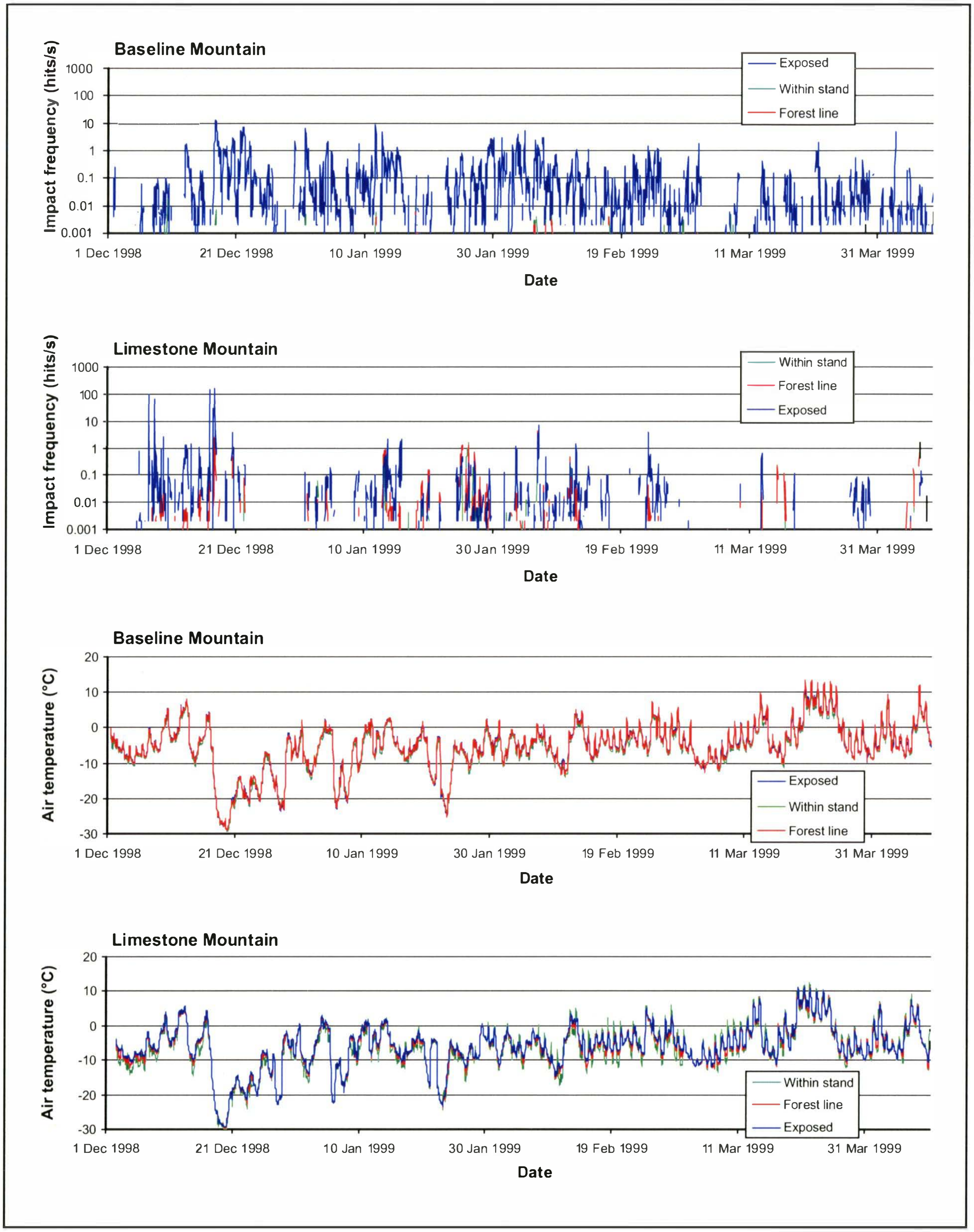

Figure 6. Hourly ice particle impact frequency and air temperature (50 cm above ground) for December 1998 to April 1999.

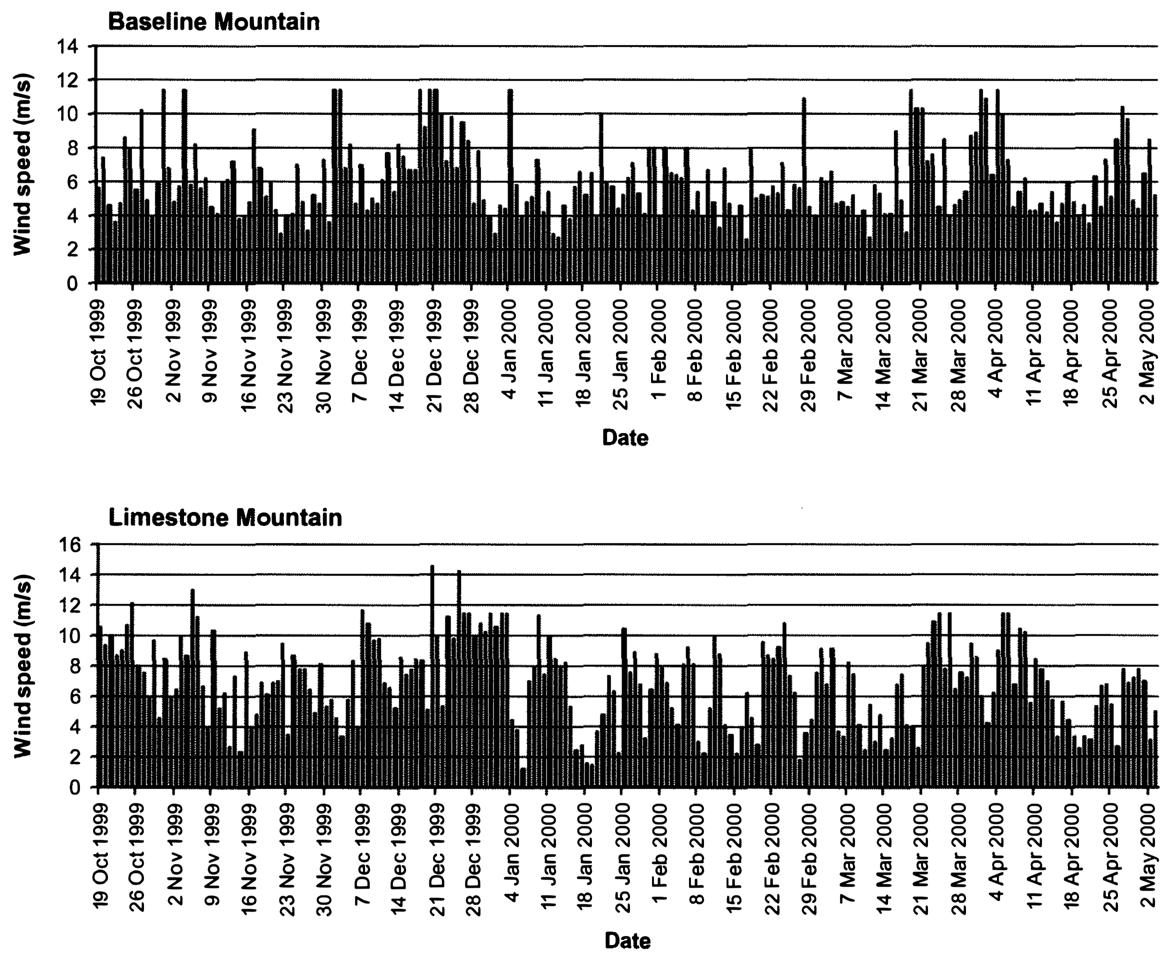

Figure 7. Full wind speed records for 1999/2000 measurement period at Baseline Mountain and Limestone Mountain sites.

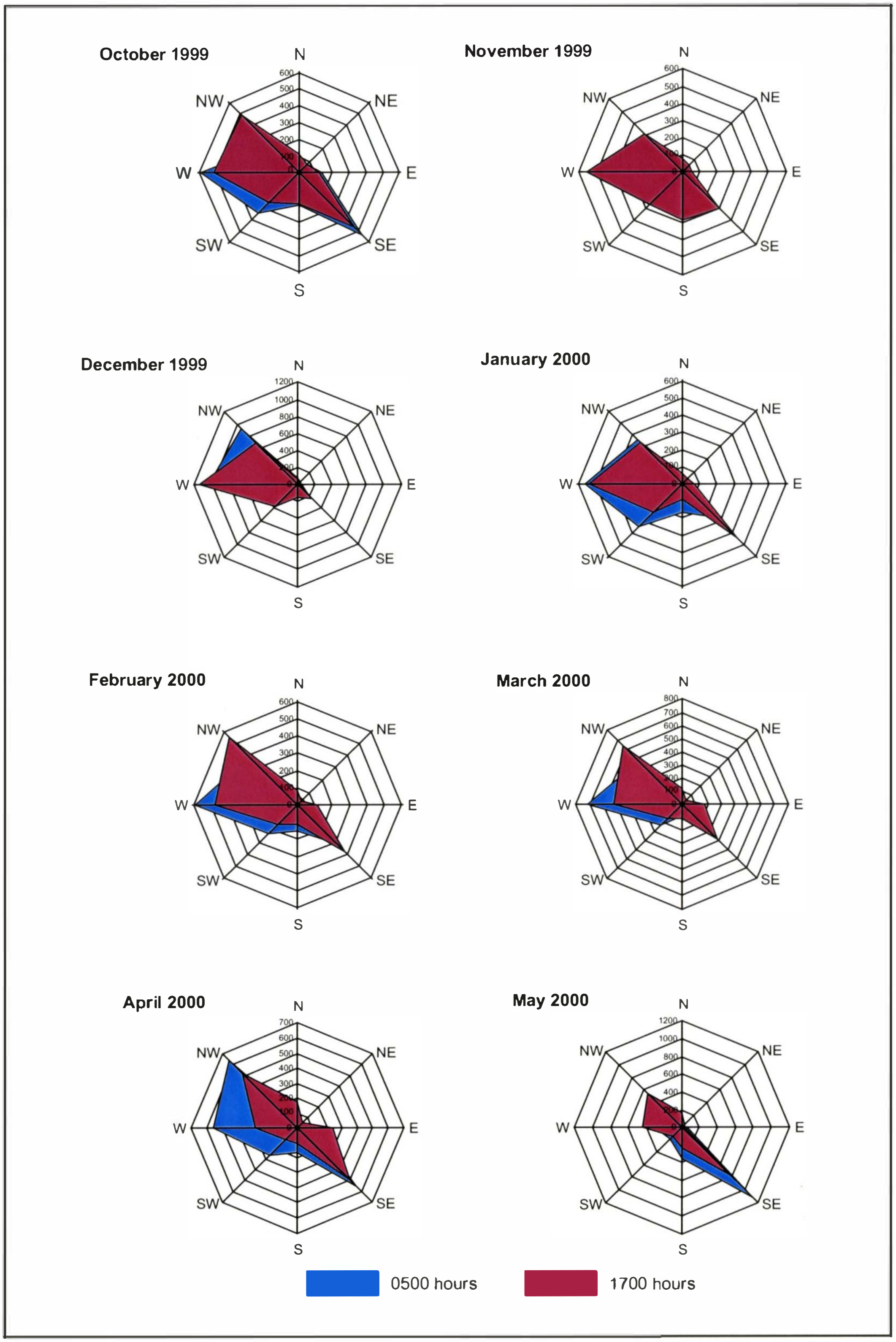

Figure 8. Wind speed (metres per second) frequency distributions for each month during the 1999/2000 measurement period on Baseline Mountain.

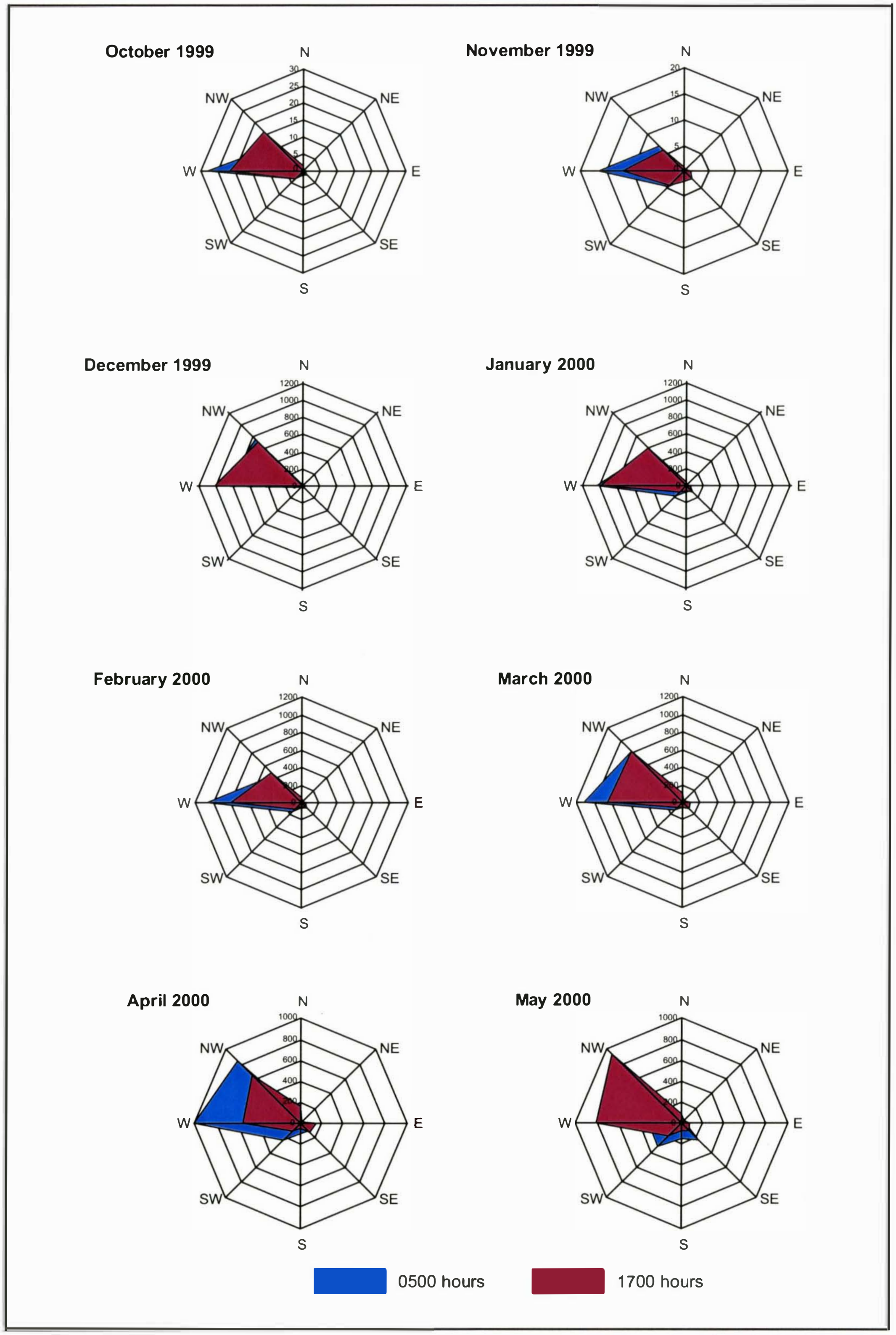

Figure 9. Wind speed (metres per second) frequency distributions for each month during the 1999/2000 measurement period on Limestone Mountain.

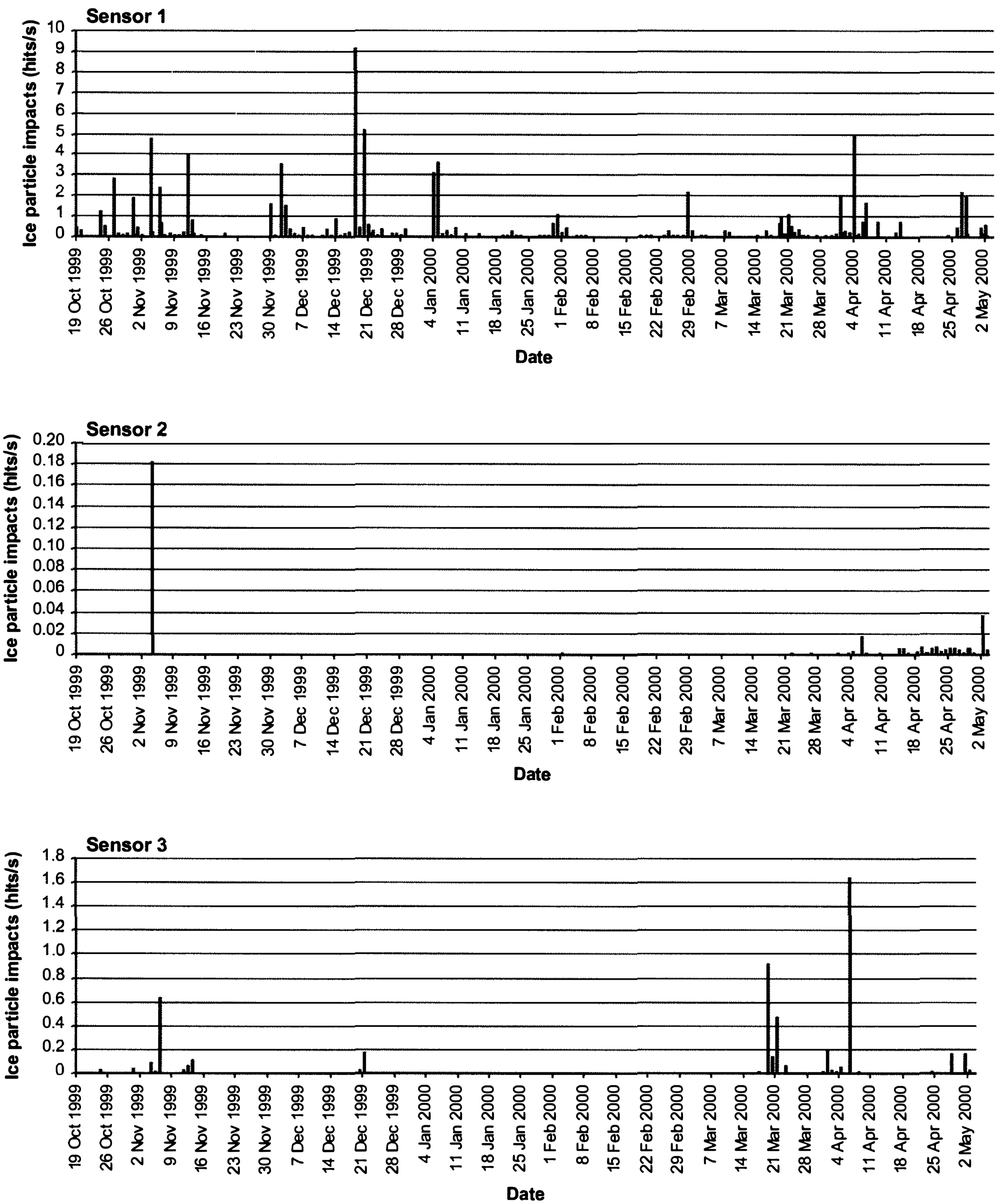

Figure 10. Full records of ice particle impacts at three locations on Baseline Mountain for the 1999/2000 measurement period.

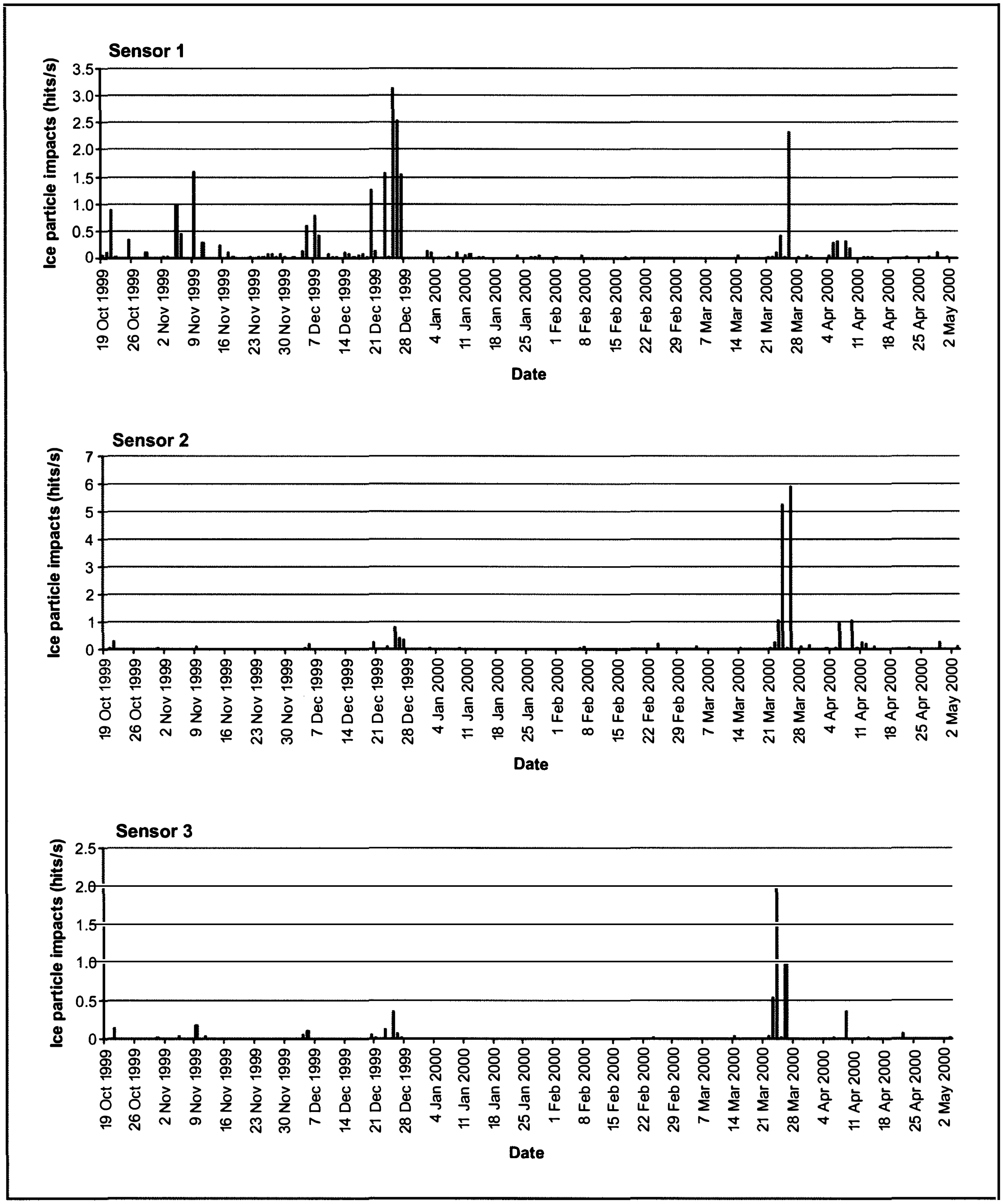

Figure 11. Full records for ice particle impacts at three locations on Limestone Mountain for the 1999/2000 measurement period.

and 14 March 2000 and was caused by small mammals browsing on the cables.

Air temperatures and wind speeds correlated well between Limestone and Baseline mountains, which confirmed the results from 1998/1999 indicating that the two sites have similar macroclimatic conditions. At both sites the full impact records for acoustic sensor 1 were clearly episodic, with at least 15 episodes for Baseline Mountain (Fig. 10) and 8 for Limestone Mountain (Fig. 11). The maximum impact value on Limestone Mountain during the 1999/2000 measurement season was approximately one-third that on Baseline Mountain. Macroclimatic variables appeared similar at the two sites, but the individual site characteristics produced variability in the acoustic sensor measurements. Furthermore, comparison of the 1998/1999 and the 1999/2000 data showed that winter conditions were variable from year to year at these sites.

Wind direction was depicted as frequency distributions of the mean wind direction weighted by wind speed graphed as wind rose diagrams. Means were calculated for each month of measurement to show site differences and seasonal fluctuations. Strong, consistent winds originated from the west and northwest at both Baseline and Limestone mountains in both the early morning and late afternoon (Figs. 8 and 9, all months). Baseline Mountain, however, had a significant proportion of wind originating from the east and southeast. Figure 12 summarizes the percentage area on the wind rose diagrams in Figures 8 and 9 that originated from the direction of the Ram River plant at both sites. From the Baseline Mountain ridge, the plant is at 90° and from the Limestone Mountain ridge, the plant is at 20°. Overall, Limestone Mountain had a lower percentage of wind from the direction of the Ram River plant. At both sites, March and April were the months when more winds came from the directions of the plant.

In addition to high-velocity wind-borne particles and extreme low temperatures, winter desiccation of needles is another factor producing damage at high altitudes. The red belt phenomenon, discussed later, in the section on tree growth, is characterized by browning of needles, an effect thought to be caused by desiccation. This occurs where temperatures are warm enough for needles to begin transpiration but the root systems remain frozen. The moisture lost by transpiration is not compensated by the root systems, and the needles die and turn brown. To capture data on periods when these conditions might have occurred, the number of freeze–thaw cycles and the periods for which temperature was above and below zero were calculated. A freeze–thaw cycle was defined as a period with temperature less than or equal to 0°C followed by a period with temperature greater than 0°C.

Table 9 shows the freeze–thaw calculations based on records from Baseline Mountain, Limestone Mountain, and Rocky Mountain House airport for the winters of 1998/1999 and 1999/2000. In all cases, data from the Rocky Mountain House airport showed more freeze–thaw cycles than either Baseline Mountain or Limestone Mountain. However, the two study sites had a higher percentage of episodes when temperatures remained above 0°C for longer than 1 h. That is, the chance of a thaw period lasting long enough for needles to begin transpiration was greater at the high-altitude sites. Red belt or winter drying conditions have also been reported frequently in valley bottoms by the Canadian Forest Service in the region (Smith 1967). As illustrated by the freeze–thaw records, the potential for winter drying conditions exists at low elevations such as Rocky Mountain House and will produce the same symptoms as red belt. Full temperature records for the 1999/2000 measurement period at the Baseline Mountain and Limestone Mountain sites are shown in Figure 13.

Table 9. Freeze–thaw cycles for Baseline Mountain, Limestone Mountain, and the Rocky Mountain House airport

Site	1998/1999		1999/2000	
	No. of freeze–thaw cycles[a]	% cycles with thaw > 1 h	No. of freeze–thaw cycles	% cycles with thaw > 1 h
Baseline Mountain (1796 m)	43	88	60	83
Limestone Mountain (2002 m)	30	86	67	73
Rocky Mountain House (1015 m)	113	61	89	76

[a] Period when temperature ≥ 0°C, followed by a period when the temperature is > 0°C.

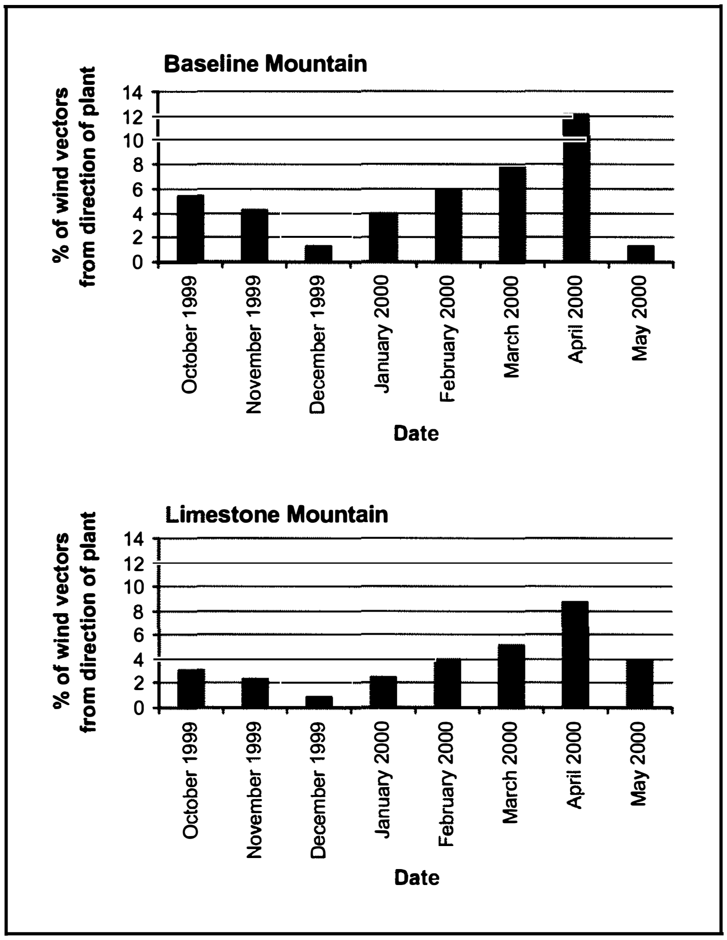

Figure 12. Percentage of wind vectors that originated from the direction of the Ram River plant. The plant is oriented at 90° to the Baseline Mountain ridge and at 20° to the Limestone Mountain ridge.

Epicuticular Wax

Two approaches were taken to studying epicuticular wax. The first was to determine the differences in the amount of epicuticular wax on planted seedlings and naturally occurring trees growing at or below forest line. The second was to observe the types of wax formations on the needles of trees growing at or below forest line. The seedling trials were not entirely successful because the seedlings planted at forest line only survived through part of the summer and were dead from exposure by the time of the spring sampling period. However, trends seen in the naturally occurring tree samples were similar to those observed in the planted seedlings.

The statistical analysis of amounts of wax revealed that the effect of position was significant. The needles of trees in the exposed (forest line) areas had significantly less wax than the needles of trees in the sheltered areas (below forest line) ($P = 0.031$). The least square means for the upper and lower locations were 0.00110 g and –0.000 068 4 g, respectively. Cuticular wax from seedlings grown in Edmonton and on Limestone and Baseline mountains was compared. There was significantly more wax on the seedlings grown on Limestone Mountain than on seedlings grown in Edmonton and on Baseline Mountain ($P = 0.05$). There was no difference in the amount of wax between Edmonton and Baseline Mountain seedlings ($P = 0.443$).

The harsh environment of the forest-line locations on both Baseline Mountain and Limestone Mountain was exemplified by the fact that 70% and 75%, respectively, of the trees planted at these sites died. None of the trees planted below forest line or in Edmonton died.

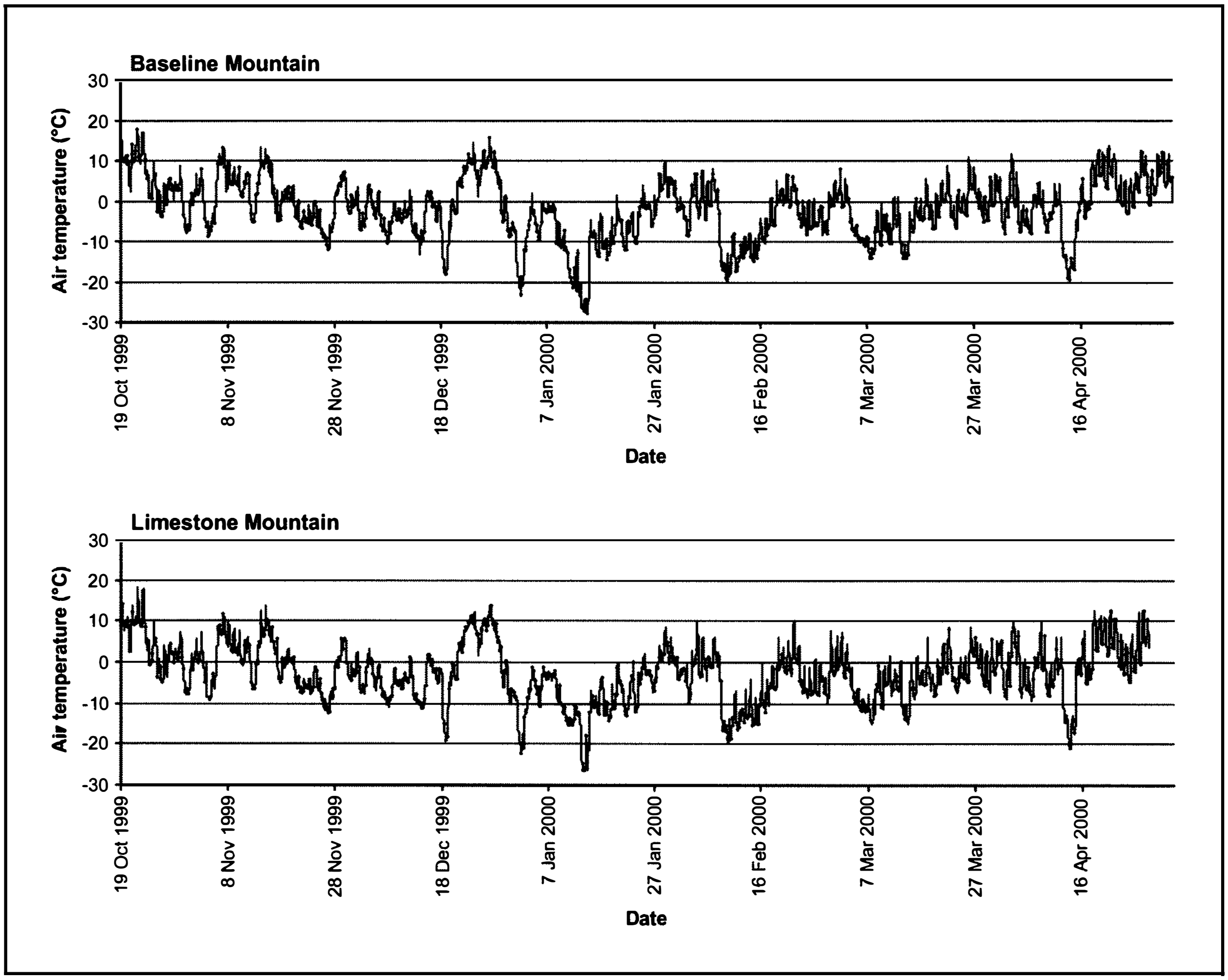

Figure 13. Full temperature records for the 1999/2000 measurement period.

Tree Health Survey

The results of the tree health survey are shown in Tables 10 and 11. Very few dead trees were observed at either the Baseline Mountain or the Limestone Mountain site. Most trees (97.0% of all trees at the Baseline Mountain site and 95.3% of those at the Limestone Mountain site) were healthy. There were no statistically significant differences between sites in the number of recently dead, declining, and healthy trees ($\chi^2 = 2.003$, $P = 0.157$).

There were proportionally almost twice as many lodgepole pine at the Baseline Mountain site (29.7%) as at Limestone Mountain site (16.1%) that showed no evidence of injury. Atropellis canker (*Atropellis piniphila* (Weir) Lohman & Cash) and western gall rust (*Endocronartium harknessii* (J.P. Moore) Y. Hiratsuka) were found on lodgepole pine at both sites. The frequency of atropellis canker at the Limestone Mountain site (52.3%) was higher than at the Baseline Mountain site (13.0%). This disease was probably responsible for some of the stem deformation, crooked stems, and forking that were observed in lodgepole pine at both sites. There was proportionally twice as much dieback, a reddening of foliage on some branch tips (Fig. 14), on lodgepole pine at the Baseline Mountain site (19.6%) as at the Limestone Mountain site (9.8%). The dieback was suspected to be a result of cankers caused by *A. piniphila*. Three trees with branch dieback at the Limestone Mountain site were cut and examined for cankers, which were found on the stems and the branches. The average number of branches and branchlets on these trees was 125.7. The average number of cankers was 3.3 on the stems and 70 on the branches. The cankers varied in size, but in some cases they girdled the branch, killing it.

Table 10. Tree species composition and health

Location and tree species	Total no. of trees	Tree condition	No. of trees	% of total within species	% of total at site
Baseline Mountain					
Lodgepole pine	143	Healthy	130	90.9	18.5
		Declining	7	4.9	1.0
		Dead 1 yr	1	0.7	0.1
		Dead > 1 yr	5	3.5	0.7
White spruce	185	Healthy	184	99.5	26.2
		Declining	0	0	0
		Dead 1 yr	0	0	0
		Dead > 1 yr	1	0.5	0.1
Subalpine fir	374	Healthy	367	98.1	52.3
		Declining	3	0.8	0.4
		Dead 1 yr	1	0.3	0.1
		Dead > 1 yr	3	0.8	0.4
Total	702	Healthy	681	NA	97.0
		Declining	10	NA	1.4
		Dead 1 yr	2	NA	0.3
		Dead > 1 yr	9	NA	1.3
Limestone Mountain					
Lodgepole pine	369	Healthy	345	93.5	62.1
		Declining	21	5.7	3.8
		Dead 1 yr	1	0.3	0.2
		Dead > 1 yr	2	0.5	0.4
White spruce	95	Healthy	94	98.9	16.9
		Declining	1	1.1	0.2
		Dead 1 yr	0	0	0
		Dead > 1 yr	0	0	0
Subalpine fir	92	Healthy	91	98.9	16.5
		Declining	1	1.1	0.2
		Dead 1 yr	0	0	0
		Dead > 1 yr	0	0	0
Total	556	Healthy	530	NA	95.3
		Declining	23	NA	4.1
		Dead 1 yr	1	NA	0.2
		Dead > 1 yr	2	NA	0.4

Note: NA = not applicable.

Table 11. Symptoms and signs of damage to trees

Location and tree species	No. of trees examined[a]	Symptom or agent	No. of trees affected	% of total	% of living trees
Baseline Mountain					
Lodgepole pine	138	None	41	29.7	29.9
		Dieback	27	19.6	19.7
		Western gall rust	19	13.8	13.9
		Atropellis canker	18	13.0	13.1
		Crooked stem	17	12.3	12.4
		Forked stem	10	7.2	7.3
		Animal or mechanical damage	9	6.5	6.6
		Dead top	8	5.8	5.8
		Other	37	26.8	27.0
White spruce	184	None	90	48.9	48.9
		Deformation	32	17.4	17.4
		Gall aphids	31	16.8	16.8
		Defoliation	30	16.3	16.3
		Other	50	27.2	27.2
Subalpine fir	371	None	248	66.8	67.0
		Defoliation	57	15.4	15.4
		Dieback	21	5.7	5.7
		Deformation	16	4.3	4.3
		Crooked stem	8	2.2	2.2
		Other	33	8.9	8.9
Limestone Mountain					
Lodgepole pine	367	Atropellis canker	192	52.3	52.5
		Animal or mechanical damage	91	24.8	24.9
		Crooked stem	74	20.2	20.2
		Western gall rust	61	16.6	16.7
		None	59	16.1	16.1
		Forked stem	46	12.5	12.6
		Dieback	36	9.8	9.8
		Dead top	13	3.5	3.6
		Other	31	8.4	8.5
White spruce	95	None	51	53.7	53.7
		Defoliation	24	25.3	25.3
		Deformation	10	10.5	10.5
		Dead branches	6	6.3	6.3
		Animal or mechanical damage	5	5.3	5.3
		Other	17	17.9	17.9
Subalpine fir	92	Deformation	52	56.5	56.5
		None	22	23.9	23.9
		Defoliation	20	21.7	21.7
		Forked stem	6	6.5	6.5
		Crooked stem	4	4.3	4.3
		Dead branches	4	4.3	4.3
		Other	9	9.8	9.8

[a] All living trees plus trees that die no more than 1 yr ago.

Figure 14. Examples of dieback on lodgepole pine at the Baseline Mountain site (a) and on subalpine fir on the north side of Baseline Mountain (b).

The percentage of white spruce trees that showed no evidence of injury was about equal at the two sites, 48.9% at Baseline Mountain and 53.7% at Limestone Mountain. Deformation of branches was common at both sites. A gall aphid (*Adelges lariciatus* Patch) was common on white spruce from Baseline Mountain but not Limestone Mountain. Defoliation due to needle rust (*Chrysomyxa* sp.) was evident at both sites.

Most (67.0%) of the subalpine fir at the Baseline Mountain site showed no evidence of damage, but only 23.9% of those at the Limestone Mountain site were undamaged. The predominant injury to subalpine fir at the Baseline Mountain site (affecting 15.4% of trees) was defoliation, thought to have been caused by a needle rust (*Puccinastrum* sp.); however, the predominant injury to this tree species at the Limestone Mountain site was branch deformation (56.5%). Branch dieback, was observed on Baseline Mountain (5.7% of trees) but not on Limestone Mountain. This symptom was also observed on subalpine fir growing on the north side of Baseline Mountain.

Many of the injuries or damage such as dieback, defoliation, and deformities, although not fatal and apparently not debilitating, were evident in both stands. Deformities such as crooked stems, dead branches, and defoliation can be attributed to naturally occurring pests such as atropellis canker, western gall rust, *Adelges*, and needle rust, as well as climatic effects. Dieback occurred on lodgepole pine and fir at both sites. It was limited to the tips of certain branches. No trees had significant dieback. It was suspected that most of the dieback was caused by *Atropellis piniphila*; however, there are several other potential causes for this symptom, including climatic damage as a result of sun scalding or desiccation in winter, or damage from rime ice or the fungal pathogen known as *Gremeniella abientia* (Lagerb.) Morelet, the causal agent of scleroderris canker. Damage from SO_2 emissions was considered unlikely, as only single branches were affected, the symptoms were not consistent with the symptoms of SO_2 damage to pine or fir (Malhotra and Blauel 1980), the symptoms were observed at both sites (for lodgepole pine), and there were proportionally more uninjured trees at the Baseline Mountain site than at the Limestone Mountain site.

Alterations to normal crown form due to wind stress were prevalent at the forest line at both sites. The proportion of species with some type of wind damage (crown form class > 1) differed between locations. White spruce were more affected at the Baseline Mountain site, where 31.5% of trees were rated as having crown form > 1, and subalpine fir were more affected at the Limestone Mountain site, where 55.4% of trees were rated as having some degree of wind deformation (Table 12). This dispersion among species of wind-shaped trees probably represents the different distributions of tree species along the altitudinal gradient rather than susceptibility of different tree species to wind damage.

The loss of needles to the windward side of wind-exposed trees is thought to result from needle drying and desiccation. Needles lose their protective coating of epicuticular wax and become more susceptible to conductive water loss (Hadley and Smith 1989). In addition, acid deposition can alter the surface wax of conifer needles, and polluted climates can be identified by comparing amounts of epicuticular wax (Cape and Percy 1998). Trees exposed to harsh climates near the forest line on Baseline Mountain may be theoretically more susceptible to SO_2 emissions because of reduced amounts of epicuticular wax as a result of environmental stress; however, the majority of trees that were rated with a crown form > 1 from both Limestone and Baseline mountains were healthy, and no typical SO_2 injury was observed. Only two declining trees at the Limestone Mountain site and four declining trees at the Baseline Mountain site were rated as having a crown form > 1. Thus, trees at the forest line at the Baseline Mountain site did not appear more stressed than those at the Limestone Mountain site.

Careful examination of replicate scanning electron micrographs revealed a variety of common wax morphologies. Wax usually occurred as a crystalline, tubular structure embedded in a smooth basal wax layer (Fig. 15d). Tubes occurred over a range of densities and thicknesses, from thick masses of tubes exhibiting distinct hollow ends (Fig. 15e) to aggregates of tubular structures interspersed over the underlying smooth-wax layer. Such aggregates were termed "rosettes" (Fig. 15a and 15b). Tubular structures also varied in terms of erosional features. Tubular structure interpreted as uneroded displayed tubes with distinct hollow ends and little evidence of fusion (Fig. 15d) whereas eroded tubular features displayed tubes with blunt ends, short lengths, and fused sections (Fig. 15c). Very highly metamorphosed features appeared as amorphous globs in the underlying smooth wax or simply as unfeatured smooth layers of wax (Fig. 15g). Some miscellaneous features were also observed, such as large, flattened, scalelike areas (Fig. 15f) and dirt particles embedded in the wax.

In general, all needles exhibited a similar distribution of three basic wax morphologies: wax tubes, rosettes, and smooth wax. Wax tubes were usually found in the stomatal openings and adjacent areas, which were usually located in low, sheltered areas of the needle topography. Rosettes and smooth wax were more common on raised, exposed areas of the needle. Both parts of Figure 16 and their insets display the gradient from rough to smooth wax forms from sheltered to exposed areas on the needle surface. Exposed areas occurred not only along the ridge tops in the midsection of the needle but also at the needle tips.

Wax morphology was more variable on the exposed ridges than in the stomatal areas. These exposed areas showed pristine wax rosettes, which did not appear degraded, scalelike structures that might originated from wax tubes, and flattened, globular structures, which also appeared degraded from their original form. A thick wax tube layer seemed always to form over the stomatal openings; however, the original wax morphology of the ridge surfaces was unclear, and it was difficult to determine what constituted a form degraded from the

Table 12. Wind damage to crown form

	Crown-form class > 1 (no. and % of total trees for the species)[a]	
Tree species	Baseline Mountain	Limestone Mountain
Lodgepole pine	35 (24.5)	26 (7.1)
White spruce	58 (31.5)	31 (32.6)
Subalpine fir	28 (7.5)	51 (55.4)

[a] No damage was rated as crown form = 1. Damaged crowns were rated from 2 to 8 (*see* Fig. 3).

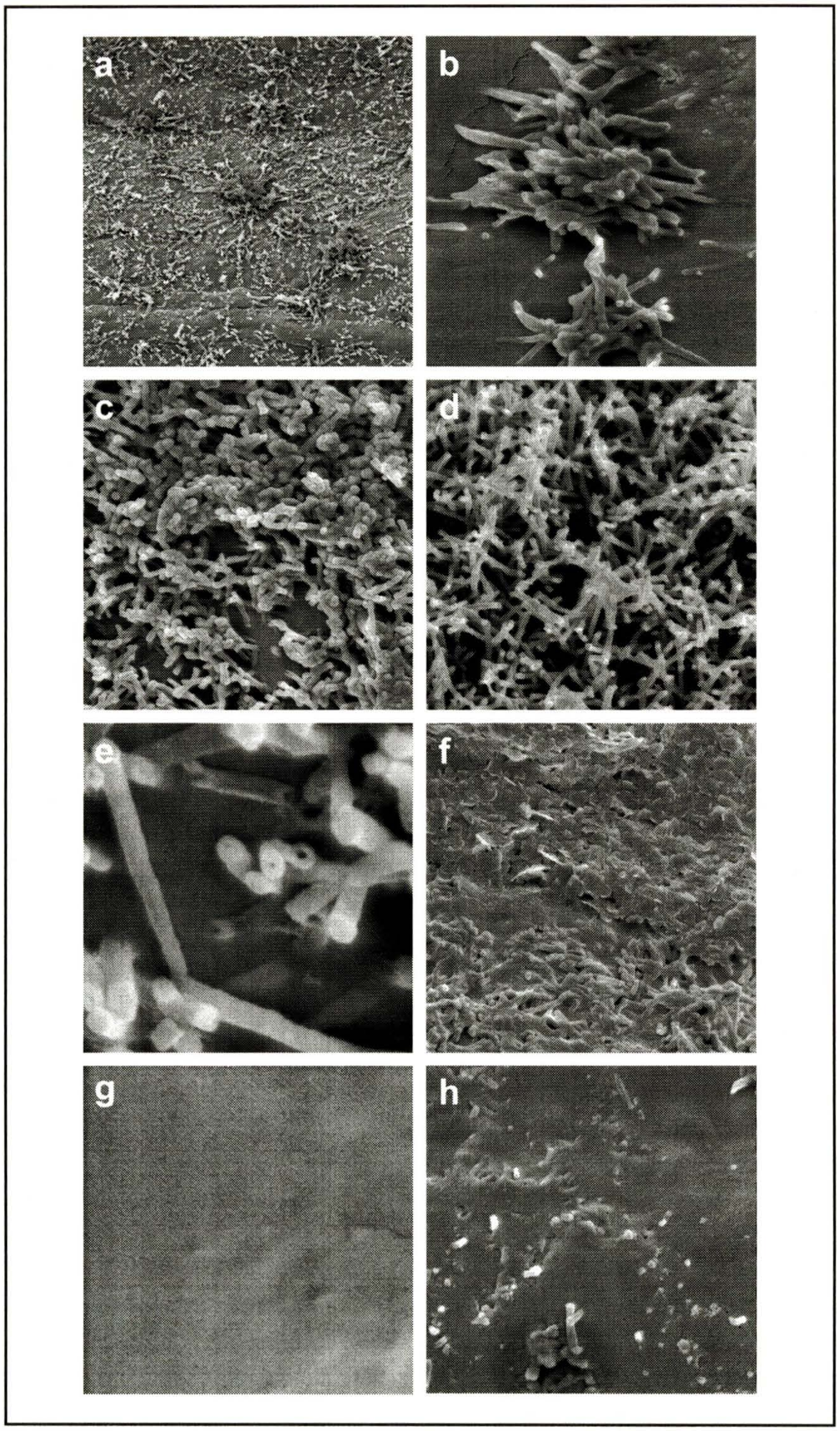

Figure 15. Examples of cuticle wax morphology on needles of planted white spruce seedlings and naturally occurring white spruce. **a)** Well-formed rosettes (370 ×). **b)** Rosette detail (10 000 ×). **c)** Lightly degraded wax tubes (10 000 ×). **d)** Pristine wax tubes (10 000 ×). **e)** Hollow tube detail (58 000 ×). **f)** Degraded tube structure and some scales (10 000 ×). **g)** Smooth wax with no structure (10 000 ×). **h)** Smooth wax with some remnants of tube wax (10 000 ×).

original. Furthermore, it was uncertain whether the smooth wax was itself a degraded surface or an original wax formation. Even with these uncertainties, the scanning electron microscopy revealed distinct patterns in distribution of wax type among the various treatments.

There was a distinct gradient from rough to smooth for the trees sampled at forest line and those taken from within the forest. The needles of both naturally occurring and planted trees at the upper sites had a smoother appearance than the needles of trees from below forest line (Figs.17 and 18). The trees in the sheltered areas had a more diffuse pattern of rough surface wax covering the stomatal areas, whereas the gradient from rough to smooth, was more distinct for trees from the upper area. An extreme case is depicted in Fig.17 (BPU), where the surface, including the stomatal areas, is almost entirely smooth. All seedlings planted in the exposed sites died sometime before or during the winter of 1999/2000.

This trend from rough to smoother surfaces was also observed for needle samples taken in the fall and in spring. Figure 16a shows a mid-needle section from a control seedling planted in Edmonton after the first summer of growth, and Figure 16b shows a needle from the same tree after the winter. Every location in the mid-needle area is smoother and appears more degraded in Figure 16b. The same trend toward smoother wax structures after the winter was observed for all needles from all locations on Baseline Mountain and Limestone Mountain (Figs. 17 and 18). It remains unclear whether these structures were undergoing metamorphosis or if the needles were laying down more smooth wax to reduce the chance of winter desiccation.

The needles taken from the control trees showed the same distribution of wax morphology and the same trend toward smoother structures after the winter. The only difference was in the amount of inorganic particles adhering to the surface (Fig 16a). There were more inorganic particles on the Edmonton samples.

Tree Growth

A reduction in tree growth may be an early sign of damage due to air pollution; however, it is rare that a direct cause-and-effect relationship can be established between pollutants and an observed reduction in growth. Even in the example of red spruce decline in the Appalachian Mountains, where an abrupt reduction in radial increments was observed after 1960, it has not been possible to directly relate the decline to concentrations of airborne pollutants (Johnson and Siccama 1983; Johnson 1992). Tree growth is strongly related to stand dynamics, genetic characteristics, forest health, and climatic conditions, and the interaction of all these factors in the environment dictates the growth response.

The index of tree growth most sensitive to air pollution in previous studies near the Ram River gas plant (Maynard et al. 1994) is the specific volume increment, obtained by calculating the average volume growth per unit area of cambium. Specific volume increment gives a measure of the growth rate for the whole tree and is thus more sensitive to environmental changes such as air pollution. It also allows the investigator to control for changes in growth rate in relation to the age of the tree.

The curve for specific volume increment plotted over the life of a tree has a characteristic shape, increasing during the first years after germination and gradually declining as the tree ages (Duff and Nolan 1953). Deviations from this characteristic curve can be inferred as representing periods when environmental stresses affected the tree. Actual growth loss can then be quantified on the basis of the year in which deviations occurred, according to equations 1 and 2. The growth loss calculation is depicted in Figure 19, where the predicted curve is calculated from the control and test profiles for the 10-yr period before damage. The growth loss is shown by the shaded area between the predicted and measured curves for the 10-yr period after damage. This method has been demonstrated by Mallett and Volney (1999) to describe the effect of Armillaria root disease on the growth of lodgepole pine.

The trees used for stem analysis in 1998 were from all elevations along the five transects and from the dominant species at each sample location. Tree age and species of trees at specific sampling locations varied along the transects and between locations, and thus the sample sizes for trees of the same species and similar ages were small (Fig. 5).

The results of the growth loss evaluation determined from average specific volume increment, as described by equations 1 and 2, are presented in Table 13. Comparisons of subalpine fir were omitted because of small sample size. The growth loss of lodgepole pine older than 68 but less than 87 yr for

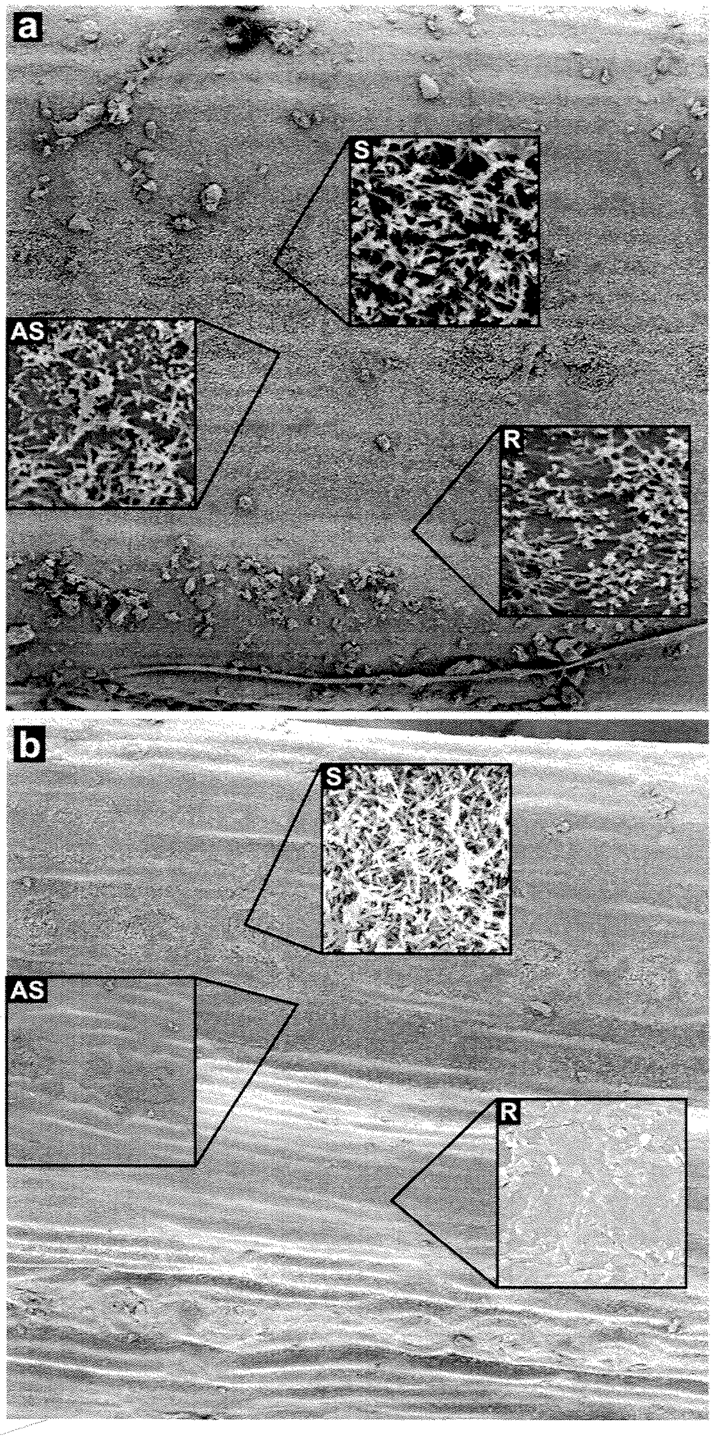

Figure 16. Comparison of needles from white spruce seedlings planted in Edmonton before and after a winter season. a) Overview of needle surface before winter (150 ×). Inset S: mid-stomata (10 000 ×). Inset AS: adjacent to stomata (10 000 ×). Inset R: exposed ridge (10 000 ×). **b)** Overview of needle surface after winter (150 ×). Inset S: mid-stomata (10 000 ×). Inset AS: adjacent to stomata (10 000 ×). Inset R: exposed ridge (10 000 ×).

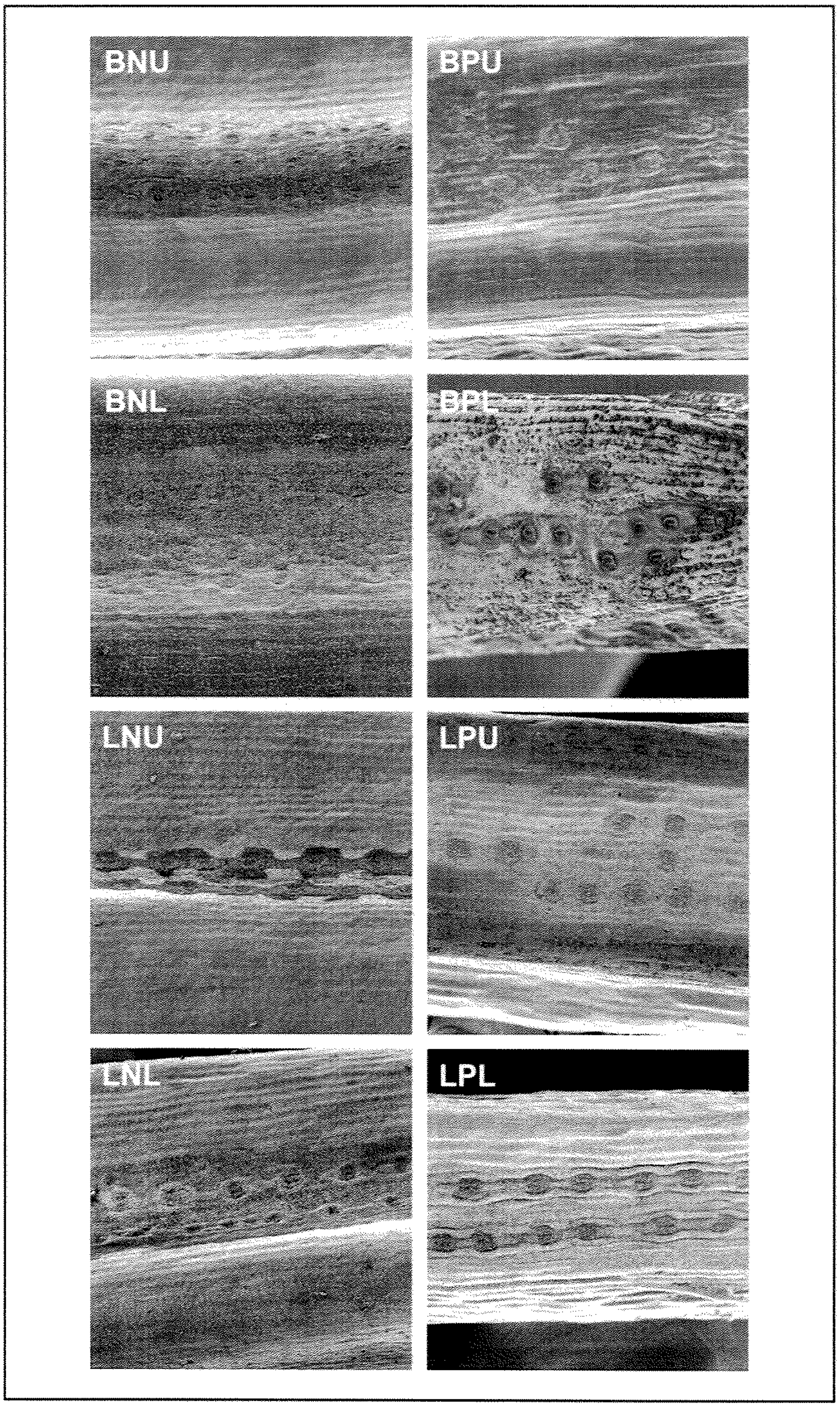

Figure 17. Epicuticular wax on needles from white spruce, fall samples. BNU = Baseline natural upper, BPU = Baseline planted upper, BNL = Baseline natural lower, BPL = Baseline planted lower, LNU = Limestone natural upper, LPU = Limestone planted upper, LNL = Limestone natural lower, LPL = Limestone planted lower. Natural = tree occurring naturally on the site, planted = seedling planted for the purpose of this study, upper = above forest line, lower = below forest line. Magnification for all images 10 000 ×.

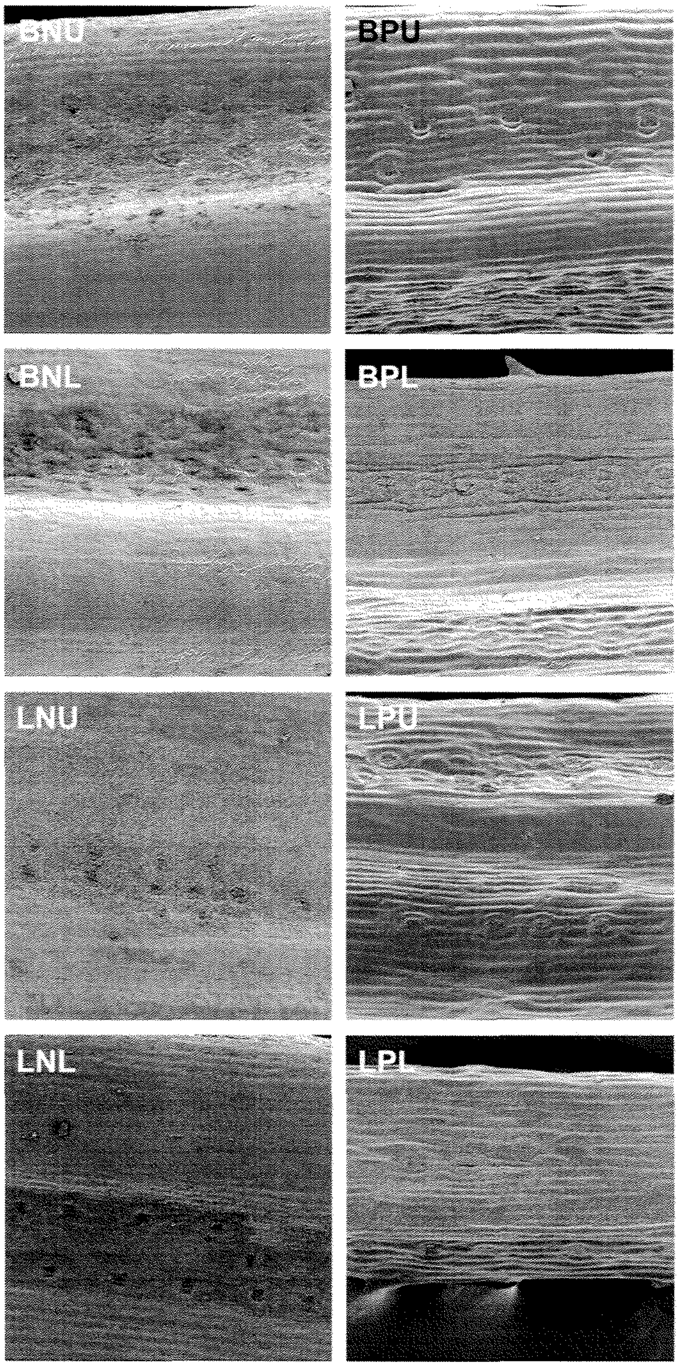

Figure 18. Epicuticular wax on needles from white spruce, spring samples. BNU = Baseline natural upper, BPU = Baseline planted upper, BNL = Baseline natural lower, BPL = Baseline planted lower, LNU = Limestone natural upper, LPU = Limestone planted upper, LNL = Limestone natural lower, LPL = Limestone planted lower. Natural = tree occurring naturally on the site, planted = seedling planted for the purpose of this study, upper = above forest line, lower = below forest line. Magnification for all images 10 000 ×.

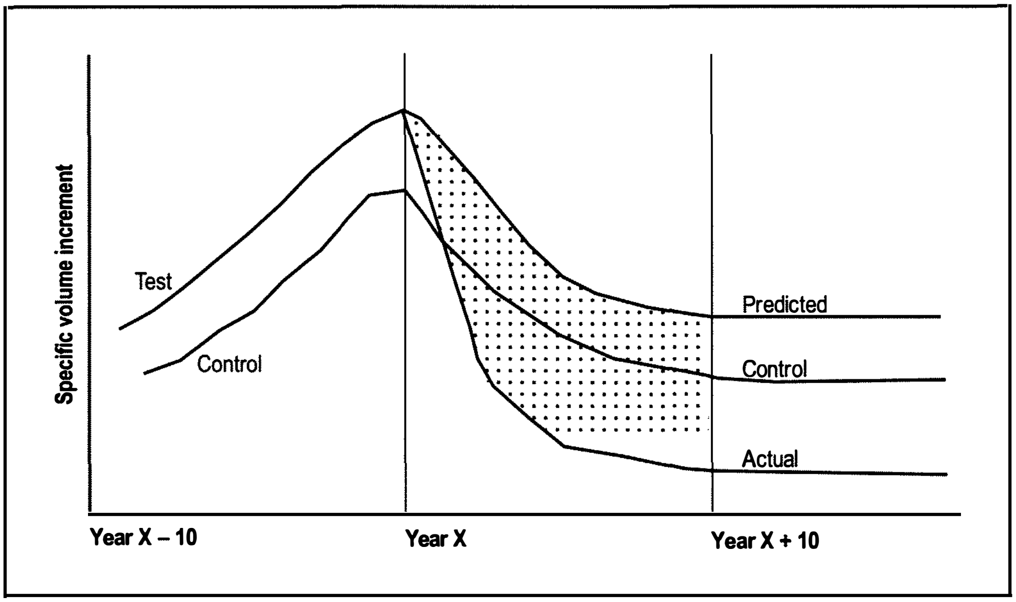

Figure 19. Diagram outlining growth loss calculations. Growth loss is represented by the shaded area.This example depicts a situation in which growth loss is calculated.

Table 13. Average specific volume growth losses in trees > 38 yr of age on Baseline Mountain

	Growth loss after 1972			Growth loss after 1985		
Species and age class (yr)	Mean growth loss (%)	Standard error	*n*	Mean growth loss (%)	Standard error	*n*
Pine						
>38	37.6	22.0	7	–5.8	9.8	7
>68 and <87	82.2	23.0	4	–5.8	12.7	4
Spruce						
>38 and <60	15.0	35.1	4	–1.2	15.9	4

the 10-yr period after 1972, 82.2%, was significant. The year 1972 was used because the Ram River plant began operations in that year; however, it is evident from the ring-width chronologies that growth efficiency declined sharply 4 years before that (Fig. 20). Trees at both study sites showed growth losses in the past, including in the 1940s and 1950s, but the cause of these losses is uncertain. Trees on both Baseline Mountain and Limestone Mountain showed a decline in 1968; however, for the trees on Baseline Mountain, growth decreased to a lower level and never recovered to its previous level.

After the initial decline in specific annual volume increment in 1968, lodgepole pine at the Baseline Mountain site did not continue to decrease in productivity, as was the case for Limestone Mountain trees. In fact, when 1985 was used instead of 1972 for the growth loss calculation, there was essentially no difference in the growth rates at the two sites (Table 13). The year 1985 was used as a halfway point in emission reductions from both the Strachan and Ram River gas plants, and it provided a 20-yr period not including 1972 for growth loss calculations. Growth increased in trees on Baseline Mountain after 1972, coincidental with start-up of the Ram River and Strachan plants.

Given that the growth loss calculated for the post-1972 period began in 1968, other environmental stresses must be considered as the cause of the

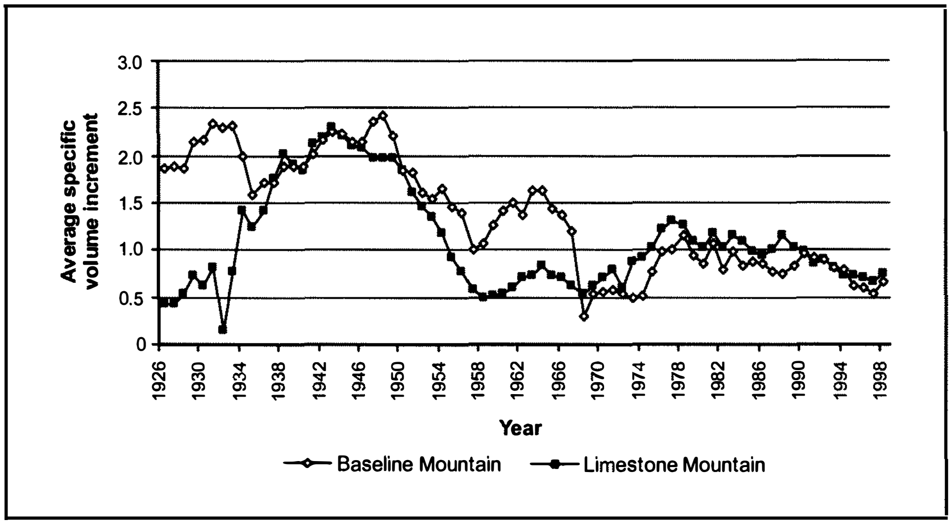

Figure 20. Plot of specific volume increment for lodgepole pine > 68 and < 87 yr at Baseline and Limestone mountains.

decline. Red belt is an environmental phenomenon that affects lodgepole pine at high elevations. It has been recorded periodically since 1950 in west-central Alberta by the Canadian Forest Service insect and disease survey. The symptoms of red belt are reddish brown needles found mainly on lodgepole pine in horizontal bands along the sides of mountain slopes (Hiratsuka and Zalasky 1993). The needles are damaged by exposure to warm, dry winds before the ground has thawed and compensatory moisture can be drawn from the soil. In late winter, a temperature inversion often occurs in the valleys of mountainous terrain, and the warm, dry Chinook winds pool above the cooler air, causing damage to trees at that elevation on mountainsides (Henson 1952). When such conditions exist, only the needles not covered in snow show discoloration, and the trees often recover the following year (Robins and Susut 1974; Hiratsuka and Zalasky 1993).

Climate data for 1967 revealed that the total monthly precipitation at Rocky Mountain House for June, July, and August 1967 was 83%, 56%, and 21% of the normal amounts for the period 1961 to 1990. Furthermore, the annual regional forest insect and disease survey for 1966 reported severe red belt in lodgepole pine stands on Corkscrew and Limestone mountains (Smith 1967). In 1967, evidence of the previous year's damage was still evident, and there were reports of more damage near Baseline Mountain lookout, Marble Mountain, and Corkscrew Mountain (Tripp and Robins 1968). Drought conditions, combined with the occurrence of severe red belt conditions in 1966 and 1967, may have caused the decline in lodgepole pine productivity that culminated in narrow rings in 1968.

In the fall of 1999, additional trees were cut from both study sites and from two new sites on the opposite slopes. These extra trees increased the sample size of even-aged lodgepole pine and allowed testing of the hypothesis that red belt was the cause of the large growth losses calculated in the 1998 analysis. If two sites separated by less than 3 km showed differences in growth patterns, then it could be concluded that red belt caused the growth losses (such damage occurs in very specific areas, on south-facing, sunlit slopes [Henson1952; Robins and Susut 1974], and the boundaries are often abrupt).

A series of four growth loss calculations were performed for various test site and control combinations as for the 1998 analysis. Analysis 1 in Table 14 compares the Baseline Mountain east test site with the Limestone Mountain east control site, as in the 1998 analysis, except that the analysis period was 10 yr after 1968 instead of 10 yr before 1972. The year 1968 was used because with the larger sample of trees we could more confidently state that 1968 was the beginning of that particular growth decline.

The result of analysis 1, a 77.4% growth loss, supports the 82% loss calculated for the smaller sample collected in 1998. The graphs in Figure 21 show the residuals for specific volume increment for each

Table 14. Average specific volume growth losses in trees from four test sites on Baseline and Limestone mountains

Analysis	Test site	Control site	Growth loss after 1968 (%)	Standard error
1	Baseline east	Limestone east	77.4	35
2	Baseline east	Baseline west	43.1	27
3	Baseline west	Limestone west	22.7	17
4	Limestone east	Limestone west	−2.5	30

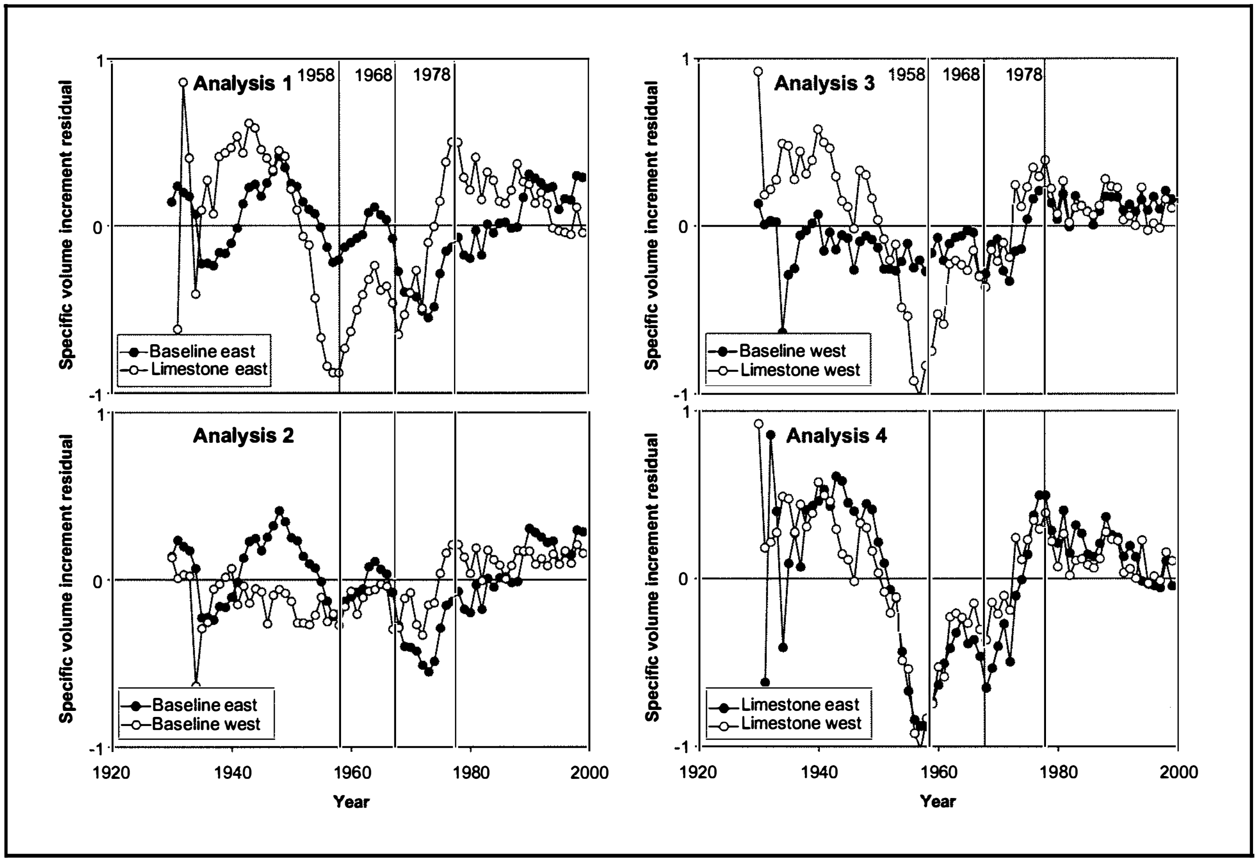

Figure 21. Residuals for specific volume increment for lodgepole pine from Baseline and Limestone mountains. The analyses correspond to those presented in Table 14.

group of 12 trees. Residuals were calculated from the best-fit conifer growth curve described by Fritts (1976, equation A). Positive residuals represent periods when environmental conditions were favorable for tree growth, and negative residuals depict periods when conditions were unfavorable. Two periods are of particular interest: the period beginning in 1968, when Baseline Mountain trees experienced large declines in growth and the period beginning in 1954, when Limestone Mountain trees experienced devastating growth losses (Fig. 21, analysis 1).

The calculated growth loss of 77.4% for the period 1968 to 1978 (Table 14, analysis 1) can be explained by means of Figure 21, analysis 1. Such a large growth loss reflects the fact that the trees at Limestone Mountain were recovering from the extreme reduction in growth in 1954 and the fact that Baseline Mountain trees did not experience decline until 1968. Limestone Mountain did experience some environmental stress during the period 1968 to 1978, but the large calculated growth loss probably reflects the fact that trees on Limestone Mountain were recovering while those on Baseline Mountain were declining.

Figure 21, analysis 2 shows that trees growing on the west side of Baseline Mountain experienced lower-than-expected growth between 1968 and 1978, but the decline was not as severe for trees growing on the east side of the mountain. There was a 43.1% growth loss for trees on the east side relative to those on the west side (Table 14, analysis 2). The decline observed on the west side of Baseline Mountain was no greater than other declines observed at that site since the early 1940s.

The growth history for trees on Limestone Mountain was very different from that for trees on Baseline Mountain (Fig. 21, analysis 3). The decline for Limestone Mountain trees in 1954 was far greater than anything observed for Baseline Mountain trees. Furthermore, comparisons of Limestone Mountain east and Limestone Mountain west (Fig. 21, analysis 4) indicated that the environmental stress responsible for such a large decline in growth was experienced at the same intensity on both sides of the mountain (Table 14, analysis 4).

There have been distinct periods of growth decline at both study sites, some common to the two sites and others unique to one site or the other. There is a record of red belt damage on Baseline Mountain occurring after spring 1967; however, there are no records of red belt occurring on Limestone Mountain in 1954. There was a recorded outbreak of the northern lodgepole needle-miner (*Coleotechnites starki* (Freeman)) in Alberta in the 1940s and early 1950s. This organism defoliates large areas of lodgepole pine forest, and the principal effect is a reduction in growth (Furniss and Carolin 1977). Although this outbreak was thought to have been confined to Banff, Yoho, Kootenay, and Jasper national parks (Stark 1954), it is possible that it reached Limestone Mountain and that the needle-miner was responsible for the growth loss.

CONCLUSIONS

This study was designed to determine whether tree symptoms observed on Baseline Mountain were due to airborne SO_2 from the Husky Ram River plant or if they were the result of natural phenomena. A site at Limestone Mountain, similar in elevation, topography, aspect, and vegetation to the Baseline Mountain site but exposed to low SO_2 emissions, was chosen for comparison. Although the Limestone Mountain site was not identical with the Baseline Mountain site in elevation and stand structure, the two sites were remarkably similar. Measurements obtained by passive SO_2 air monitoring and snow analysis showed statistically significantly greater (although not necessarily biologically significant) SO_2 at Baseline Mountain than at Limestone Mountain; however, the SO_2 concentrations were below the federal limit of 10 ppb. Soil and foliar analyses for S indicated very few differences in S concentration between the two sites. The tree health survey did not show any differences in mortality or decline of trees at the two sites. No trees showed any symptoms of SO_2 injury. There were some differences in pest damage (e.g., atropellis canker in lodgepole pine). Microclimate monitoring showed that similar weather events occurred at the two sites, at least during the two winters when monitoring occurred. Experiments to determine the effect of abrasion on the epicuticular wax of white spruce showed that trees grown at forest line had less epicuticular wax after winter than trees grown below forest line. Lodgepole pine on Baseline Mountain showed a highly significant decrease in specific volume increment relative to lodgepole pine on Limestone Mountain, probably because of red belt damage. The decline in specific volume increment began in 1968, before the Ram River plant was opened. Since that time, specific volume increment has steadily increased in trees on Baseline Mountain.

Given this evidence, it is unlikely that SO_2 was responsible for the reddening of foliage and dieback of trees at forest line that was observed in 1996. Tree-ring records, tree health survey data, microclimate information, and experimental evidence from wax abrasion studies indicate that the damage was more likely caused by naturally occurring phenomena rather than by pollution.

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Appendix 1
Soil profile descriptions and chemical analyses

Soil profile description[a]

Horizon	Depth (cm)	Color (moist)	Soil texture[b]	Roots (size; no./dm^2)	Coarse fragments (% by volume)[c]
Baseline Mountain					
L	13–12				
F	12–1				
H	1–0				
Aej	0–3	7.5YR 6/6	CL	2–5 mm; 1–10	10
Bm1	3–12	7.5YR 5/6	SiCL	2–5 mm; >10	10
Bm2	12–30	10YR 3/3	SiL	1–2 mm; >10	30
Bmk1	30–47	10YR 3/4	L	<1 mm; >10	40
Bmk2	47–66	2.5Y 5/4	L	<1 mm; >10	60
BCk	66–75	5Y 4/4	SL	None	80
Ck	75–92+	2.5Y 6/2	SL	None	90
Limestone Mountain					
L	4–3				
F	3–0				
Ae	0–6	10YR 7/1	SiL	1–2 mm; >10	20
Bm1	6–23	10YR 5/6	L	<1 mm; >10	40
Bm2	23–42	2.5Y 5/4	SCL	1–2 mm; <10	80
BC	42–70+	2.5Y 4/4	SCL	None	90

[a] For both sites, the parent material was colluvium and Eluviated Dystric Brunisol.

[b] Determined by particle size analysis.

[c] Visual estimate.

Chemical analyses[a]

Horizon	Depth (cm)	pH ($CaCl_2$)	Total C (%)	Total N (%)	CEC (cmol/kg)	Ca (cmol/kg)	Mg (cmol/kg)	K (cmol/kg)	Fe[b] (cmol/kg)	Mn[b] (cmol/kg)	Al[b] (cmol/kg)
Baseline Mountain											
L	13–12	3.78	39.90	0.54	52.34	6.34	5.58	1.13	0.02	0.46	2.24
F	12–1	3.33	45.60	1.28	90.90	23.61	4.37	1.84	0.17	0.04	2.84
Aej	0–3	4.17	3.91	0.15	35.70	13.08	4.52	0.20	2.59	0.44	6.60
Bm1	3–12	5.00	5.91	0.19	42.98	20.70	9.24	0.18	4.11	0.41	7.81
Bm2	12–30	4.92	6.76	0.21	25.56	19.49	7.37	0.14	2.15	0.21	6.08
Bmk1	30–47	4.75	7.67	0.10	13.52	11.08	5.48	0.07	0.71	0.10	4.50
Bmk2	47–66	5.05	7.79	0.05	10.14	13.10	3.29	0.08	0.46	0.08	3.82
BCk	66–75	5.12	8.69	BD[c]	5.14	11.03	2.27	0.02	0.22	0.05	3.07
Ck	75–92+	5.21	14.14	BD	1.48	5.47	3.78	BD	0.13	0.03	2.89
Limestone Mountain											
L	4–3	3.64	48.78	0.41	58.76	6.58	4.72	0.97	0.03	2.00	4.24
F	3–0	3.61	41.90	1.60	37.80	12.61	3.03	2.50	0.31	1.28	5.76
Ae	0–6	3.22	2.48	0.09	12.31	1.58	0.45	0.09	0.73	0.04	4.36
Bm1	6–23	3.46	1.24	0.05	9.91	1.49	0.42	0.02	0.94	0.01	5.15
Bm2	23–42	3.46	1.09	0.05	9.94	0.82	0.30	0.04	2.13	0.02	7.33
BC	42–70+	3.76	0.99	0.03	7.61	0.59	0.23	0.01	1.45	0.04	7.04

[a] Analytical methods as described for soil analyses.

[b] Pyrophosphate-extractable (Kalra and Maynard 1991).

Note: CEC = cation exchange capacity, BD = below detection.