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Microclimate Studies in Silvicultural Systems on the Chilcotin Plateau of British Columbia

The Itcha–Ilgachuz Project (1997–2003)

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Robert M. Sagar, Michaela J. Waterhouse, and
Bill Chapman

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Prepared by
Robert M. Sagar, Biometeorology Consultant
Box 25, Tatlayoko Lake, BC V0L 1W0
and
Michaela J. Waterhouse
B.C. Ministry of Forests, 200-640 Borland St., Williams Lake, BC V2G 4T1
Michaela.Waterhouse@gems4.gov.bc.ca (corresponding author)
and
Bill Chapman
B.C. Ministry of Forests, 200–640 Borland St., Williams Lake, BC V2G 4T1
Bill.Chapman@gems8.gov.bc.ca

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ABSTRACT

Group selection and irregular group shelterwood silvicultural systems are being tested as options to conserve woodland caribou (*Rangifer tarandus caribou*) habitat. If successful, the systems will be applied within the very dry, cold Sub-Boreal Pine–Spruce (SBPSxc) and very dry, very cold Montane Spruce (MSxv) biogeoclimatic subzones, located on the high-elevation Chilcotin Plateau of west-central British Columbia. In these harsh growing environments, partial cutting strongly influences the microclimate in terms of air and soil temperature, frost events, and snow-free dates.

To examine the magnitude of this influence, three pairs of climate stations were set up in partial cuts and clearcuts, across a range of elevations, to compare microclimate conditions. Over the 7-year sample period, all blocks had frequent and sometimes severe (air temperature <-4°C) frosts throughout the growing season. As many as 58 frosts (<0°C) out of 76 nights during the period 1 June–15 August were recorded at one block. Minimum air temperatures of -12.4°C in June and -10.5°C in July were recorded. Partial cuts substantially reduced the number and severity of frosts over clearcuts; however, soil temperature and soil temperature index (STI) were lower in partial cuts than the nearby clearcuts. Mean growing-season (15 cm) soil temperatures were less than 10°C at all locations, with clearcuts being 1.5–1.9°C warmer than nearby partial cuts. Snow-free dates were approximately 1 month later at the highest-elevation site (1620 m) in comparison to the lowest site (1290 m). This lowered soil temperatures and shortened growing seasons at the highest site. Heavier snowpacks virtually eliminated soil freezing at the highest site.

The study also compared north edge, centre, and south edge microsites within one 30-m opening on each of three partial cuts. The north edge (south aspect) was the most favourable microsite for seedling growth in the partial cuts, with the highest soil temperatures, earlier snow-free dates, and more solar irradiance. Low soil temperatures and light levels made the south edge (north aspect) the least favourable microsite.

Group selection and irregular shelterwoods may be applied to 181 000 ha of northern caribou habitat. Results of this microclimate study show that partial cutting clearly modifies the growing environment for lichen, tree regeneration, mushrooms, and others species. The proposed systems show promise in their ability to maintain caribou habitat and allow for some timber harvesting.

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We would like to thank Bob Stathers, who did the original weather station installations, and the subsequent maintenance and data reporting from 1997 to 2000. We also acknowledge Teresa Newsome, who provided advice on the climate station installation and summarization of the data, and Harold Armleder, who was instrumental in developing the harvesting systems and research trial.

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1 INTRODUCTION

Lodgepole pine (*Pinus contorta*) forests in the very dry, very cold Montane Spruce (MSxv) and very dry, cold Sub-Boreal Pine – Spruce (SBPSxc) biogeoclimatic subzones represent a significant portion of the forest in the Chilcotin. Many of these forests are important habitat for northern caribou, an ecotype of woodland caribou (*Rangifer tarandus caribou*). Within the Cariboo – Chilcotin Land Use Planning Area, northern caribou are considered to be a key management species, and under the federal *Species at Risk Act* they are considered threatened. In winter, caribou prefer mature lodgepole pine forests with large amounts of terrestrial lichen and low snow depths that allow easy cratering. They also inhabit forests where arboreal lichens are concentrated. Arboreal and terrestrial lichens are consumed in nearly equal amounts throughout the winter (Cichowski 1989).

Clearcutting is the most commonly used silvicultural system in lodgepole pine forests. This silvicultural system removes the arboreal lichen and damages terrestrial lichen through physical disturbance, slash loading, lost substrate, and increased solar radiation (Miège et al. 2001). Arboreal lichen dispersal is slow and it may take many decades before a regenerating stand in a clearcut develops the canopy architecture and microclimate necessary to support lichen in amounts comparable to old stands (Stevenson et al. 2001). For these reasons, silvicultural systems based on partial cutting are being tested. They can potentially reduce the impact of harvesting on caribou habitat, including the effects on important lichen forage species.

Any harvesting of timber affects microclimate by increasing solar irradiance at the soil surface, and warming the soil (Chen et al. 1993; Bhatti et al. 2000). Harvesting increases the receipt of precipitation at the soil surface by eliminating interception of rain and snow by the forest canopy. Also, harvesting can cause an increase in damaging summer frost events due to the loss of the forest sheltering effect (decreased long-wave radiation at the surface). Under a forest canopy, a portion of the long-wave radiation emitted from the surface is absorbed and re-radiated toward the surface and not lost to the open sky.

The temperature of both the air and soil are important environmental factors that could affect the survival and growth of trees and lichen. Summer frost has been identified as a serious problem in some high-elevation tree plantations (Stathers 1989; Steen et al. 1990). The physiological effects of frost on seedlings have been studied (Delucia and Smith 1987; Lundmark and Hallgren 1987). Dang et al. (1992) found that the combination of a hard frost and subsequent exposure to high levels of direct solar irradiance on a seedling the next day is especially damaging. Conversely, shading after the frost enhances recovery by limiting excess trapped light energy within needles. Low soil temperature affects the growth and vigour of seedlings by hampering root uptake of water and nutrients, thereby decreasing the seedling's ability to photosynthesize (Delucia 1986). Lajzerowicz et al. (2004) showed that growth and photosynthesis in Engelmann spruce and subalpine fir seedlings decreased as soil temperature decreased, within the range of 5–15°C.

In frost-prone areas, Stathers (1989) suggests that partial cutting will improve the success of planted and natural regeneration compared to clearcutting because of the sheltering effects of the retained forest. It has been found that clearcut patch size (and therefore proximity to the uncut forest) greatly affects nighttime minimum air temperatures near the ground (Pettersen 1993; Groot and Carlson 1996). Frost damage was found to be greatest near the centre of the larger openings in the latter study. Jordan and Smith (1995) also demonstrated this sheltering effect in a subalpine meadow.

1.1 Microclimate Study Objectives

The objective of this study was to collect microclimate data to help explain partial cut versus clearcut differences in survival and growth of tree regeneration and lichens, and abundance of commercial mushrooms (black morel and pine). Specifically, the study will compare: (1) the clearcut and partial cut environments; (2) the north edge, centre, and south edge microsites in small partial cut openings (30 m in diameter); and (3) three blocks located along an elevational gradient from the SBPSxc to the MSxv.

2 METHODS

2.1 Site Description

The study area is located about 110 km northwest of Alexis Creek, B.C., on the Chilcotin Plateau, in west-central British Columbia. The five study blocks in the main trial are situated within 30 km of Satah Mountain (52° 28' N, 124° 43' W). For the microclimate study, three of the five blocks were selected to cover the elevational range of the study area (1290–1620 m) (Figure 1) and two biogeoclimatic zones. Block 1 (1290 m) is in the Sub-Boreal Pine–Spruce Very Dry Cold (SBPSxc), while blocks 3 (1420 m) and 5 (1620 m) are in the Montane Spruce Very Dry Very Cold (MSxv) biogeoclimatic subzone. The blocks are spread from east to west over about a 30 km distance. The clearcuts (blocks 1, 3 and 5) and partial cuts (blocks 1 and 3) are flat, while the block 5 partial cut is on an east aspect with 7–20% slope. The forest canopy throughout the study area is almost exclusively lodgepole pine. The stands are even-aged, ranging from 160 to 250 years old. Soils within all blocks are Orthic Dystric Brunisols with a sandy loam texture on glacial till parent

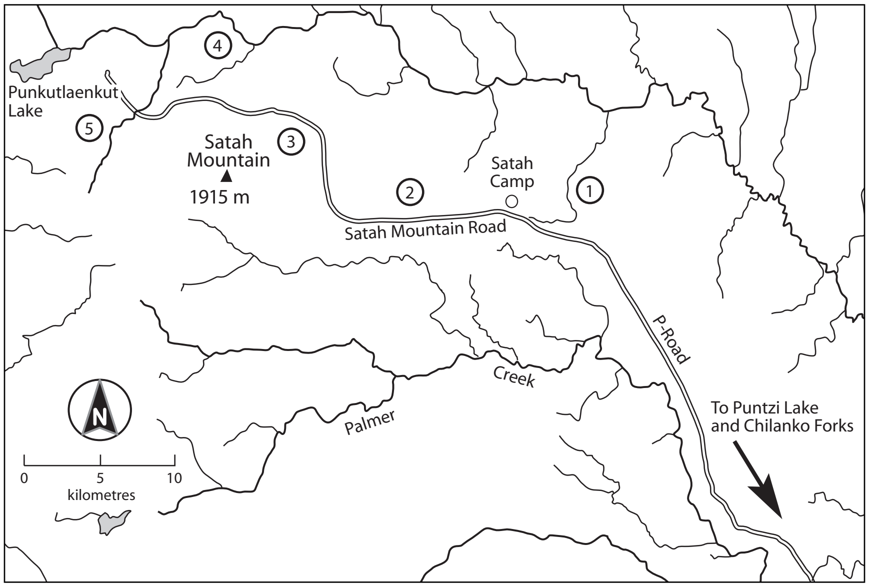

FIGURE 1 *Map showing locations of blocks 1–5, in the vicinity of Satah Mountain.*

material. In the SBPSxc, the forest floor is mostly less than 3.0 cm thick, while in the MSxv it is 3.5–6.5 cm.

The MSxv subzone occurs at middle to upper elevations surrounding the Itcha and Ilgachuz Mountains and at mid elevations on the eastern slopes of the Coast Mountains. In the MSxv study blocks, the Lodgepole Pine–Grouseberry–Feathermoss site series (MSxv/01) is predominant. Here, understory vegetation is dominated by low-growing forbs, dwarf shrubs, mosses, and lichens. Crowberry (*Empetrum nigrum*) and grouseberry (*Vaccinium scoparium*) are characteristic species, and a nearly continuous cover of mosses (*Pleurozium schreberi, Ptilium crista-castrensis,* and *Dicranum* spp.) is present (Steen and Coupé 1997).

The SBPSxc subzone occurs at elevations below the MSxv subzone, along the inside of the Coast Mountains, and extends as far north as the Rainbow Range. In block 1, the predominant site series is Lodgepole Pine–Kinnikinnick–Feathermoss (SBPSxc/01). Understory vegetation is low-growing and dominated by kinnikinnick (*Arctostaphylos uva-ursi*), pinegrass (*Calamagrostis rubescens*), and a rich variety of lichens, primarily *Cladonia* species (Steen and Coupé 1997).

2.1.1 Biogeoclimatic zone characteristics Table 1 shows some general climate characteristics of the SBPSxc, MSxv, and adjoining biogeoclimatic units (Reynolds 1997). The only climate data available for the MSxv unit are for the mean annual precipitation (MAP). The IDFdk4, SBPSxc, and MSxv units comprise an elevational transect starting southwest of Satah Mountain in the Chilanko River valley, at approximately 915 m, and rising to 1640 m in the vicinity of Satah Mountain. Along this transect, climatic conditions become wetter and cooler with increasing elevation. The MAP in the IDFdk4 is 362 mm and the mean annual temperature (MAT) is 3.2°C. Moving upwards in elevation to the SBPSxc unit, MAP increases to 413 mm and MAT falls to 1.1°C. Precipitation increases still further to 563 mm in the MSxv unit, and although no MAT temperature data are available for the MSxv unit, we can

TABLE 1 *Comparison of climate characteristics of biogeoclimatic units for study sites and other regional units (data from Reynolds 1997). A key to the heading abbreviations is listed below.*

Unit	ELE	MAP	MSP	MWP	MAT	MTCM	MTWM	T>10	T<0	NFFD	FFP
MSxv	1481.0	563.0									
SBPSxc	1168.6	413.2	189.9	221.5	1.1	-11.4	11.2	2	5	87	14
SBPSmc	968.0		176.1		0.7	-12.9	10.9	2	5		
SBPSdc	823.2	507.8	275.1	232.7	1.9	-13.5	13.9	3	5	152	61
IDFdk4	1065.5	362.4	169.4	199.4	3.2	-9.3	13.5	3	5	132	46
SBSmc2	926.7	574.7	227.9	354.0	1.5	-12.6	12.3	3	5	151	116

Key to column headings

ELE	Elevation
MAP	Mean Annual Precipitation (mm)
MSP	Mean Summer Precipitation May–September (mm)
MWP	Mean Winter Precipitation October–April (mm)
MAT	Mean Annual Temperature (°C)
MTCM	Mean Temperature Coldest Month (°C)
MTWM	Mean Temperature Warmest Month (°C)
T>10	Number of Months with Mean Temperature >10°C
T<0	Number of Months with Mean Temperature <0 °C
NFFD	Number of Frost-Free Days
FFP	Frost-Free Period

infer that they would be lower than for the SBPSxc; probably less than 0°C. The low annual precipitation of the study area reflects the position of Satah Mountain in the rain shadow of the Coast Range. For comparison, Bella Coola, (approximately 100 km to the west of Satah Mountain) on the windward side of the Coast Range, has a MAP of 1614 mm.

The number of frost-free days (NFFD) and frost-free period (FFP) decrease markedly when moving uphill from the IDFdk4 to the SBPSxc. The FFP decreases from 46 days in the IDFdk4 to only 14 days in the SBPSxc. Data presented later in this publication will show that a conventional frost-free period may not exist at our study sites.

2.2 Study Design and Treatments

The main research trial was set up based on a randomized block design. The five blocks were selected from a number of operational blocks scheduled and approved for harvesting. Each study block (60–80 ha) was split into four treatment units (15–20 ha each) and randomly assigned a silvicultural system:

- no harvest;
- irregular group shelterwood system with stem-only harvesting (IGS-SO or T1);
- irregular group shelterwood system with whole tree harvesting (IGS-WT or T2); or
- group selection with whole tree harvesting (GS or T3).

The irregular group shelterwood systems target a 50% area removal every 70 years, using openings of about 30 m in diameter. This system is intended for terrestrial lichen sites because the residual forest should provide a sheltering effect for the lichen in the openings. The group selection system, developed for arboreal lichen sites, is based on 33% area removal every 80 years, and opening sizes 15 m in diameter. A diagram of these treatment units within block 5 is shown in Figure 2.

For this study, only the IGS-WT (T2) treatments from blocks 1, 3, and 5 were utilized. Harvesting on the trial blocks was completed in April 1996. In both irregular group shelterwood (IGS) treatments, the area cut averages 39%, gaps are up to 30 m wide, and skidtrails are 3–4 m wide. One gap from each block was randomly selected for microclimate monitoring.

Clearcuts were not part of the original study design but were added to provide comparisons to partial cuts for the planted stock, natural regeneration, lichen, and microclimate studies. Each clearcut is large (>30 ha), and located adjacent to blocks 1 and 3, but about 1.2 km distant from block 5. Clearcuts paired with blocks 1 and 5 were harvested within 6 months of the trial. The clearcut paired with block 3 was cut 1.5 years prior to the partial cuts. The soil type, elevation, slope, and aspect of the clearcuts are very similar to the partial cuts, except at block 5. The climate station in the paired clearcut for block 5 is on a slight north-facing slope (2%), while the one in the partial cut is on an east-facing slope (8%). All the clearcut microclimate stations were located at least 50 m from the forest edge.

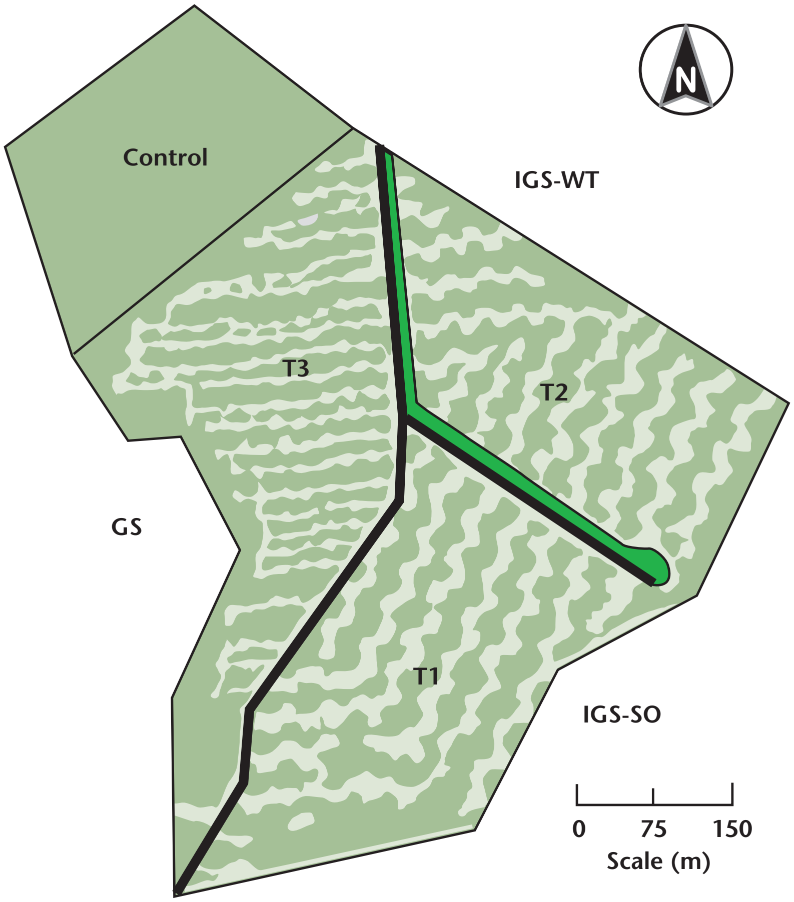

FIGURE 2 *Global Positioning System (GPS) map showing layout of partial cut treatments in block 5. (Control = unharvested, GS = group selection, IGS-SO = irregular group shelterwood – stem-only harvesting, and IGS-WT = irregular group shelterwood – whole tree harvesting.)*

2.3 Weather Station Instrumentation

The instrumentation at each station included unshielded thermistors mounted at 15 cm above the ground for measuring air temperature, and soil temperature thermistors at 1 and 15 cm beneath the mineral–organic interface. The thermistors were Campbell Scientific (Edmonton, Alberta), Model 107 sensors, covered in black or white shrink tubing (effective diameter of 5 mm), or conically shaped and potted in a clear epoxy resin (effective diameter of 10 mm). Soil water potential was measured at depths of 3 and 15 cm beneath the mineral–organic interface using gypsum blocks (Campbell Scientific, Model 207). Rainfall was measured in the clearcuts only, using tipping bucket rain gauges (Texas Electronics Inc., Dallas, Texas, Models TE525 or TE525m).

Within each clearcut, soil and air temperatures were monitored at two locations, whereas soil moisture and precipitation were monitored in one location only. For reporting purposes, an average of the two locations was used for soil and air temperatures. In the partial cut treatments, soil and air temperatures were monitored at one location in each of the three microsites. The microsites were located approximately 10 m apart in 30 m wide openings at the north-edge, centre, and south edge. Edge microsites were generally within 5 m of the canopy drip line. Soil moisture measurements were made only at the north-edge microsites of the partial cuts.

Monitoring of microclimate began at blocks 1 and 3 in 1997, and in 1998 at block 5. Soil moisture monitoring was added to the blocks in June 1999, while rain gauges were added to the clearcuts in June 2000.

2.3.1 Effects of radiation error on air temperature measurement The basic premise of air temperature measurement is to put a sensor in the environment to be measured, where it will equilibrate with the temperature of the air in that environment through convective and conductive heat transfer. However, the unshielded thermistors used to measure air temperature are subject to significant radiation errors. Radiation error is a measurement error introduced into air temperature measurements when convective heat transfer to or from the sensor is unable to equilibrate sensor temperature with air temperature due to radiative loading. The magnitude of radiation error is dependent on sensor size, shape, and colour, as well as windspeed and radiative loading on the sensor. Generally speaking, radiation error increases with sensor size due to less effective convective heat transfer for larger objects. Radiation error is typically positive during the day (sensor temperature elevated above air temperature) and negative at night.

During the summer of 2003, an experiment was carried out to assess the magnitudes of radiation errors for the unshielded thermistors (R. Sagar, unpublished data, 2003, B.C. Ministry of Forests, Williams Lake, B.C.). Fine wire thermocouples (30 AWG [American wire guage] twisted and soldered, with an effective diameter of 0.5 mm) were installed at each weather station. Due to their small diameter, radiation error is small for fine wire thermocouples (FWTCs). The results showed that radiation errors in the range of +6 to 8°C were typical for the black and conical epoxy thermistors during the day. Daytime errors for the white, shrink tube thermistor averaged only 1.2°C. Nighttime errors averaged about -0.5°C for all thermistor types. Due to the high daytime errors, daily maximum and mean air temperature data were not utilized in the data summaries.

2.4 Data Collection

Campbell Scientific, Model CR10X dataloggers recorded sensor outputs at each station. Dataloggers were powered by two 6V lantern batteries wired in series to produce 12V, and housed in watertight fiberglass enclosures. The batteries were replaced in the spring and fall of each year. The dataloggers recorded all sensor outputs once every 5 minutes. These measurements were processed by the datalogger to produce daily maximums, minimums, and averages for all air and soil temperature sensors. For the rain gauges, the datalogger output was daily total rainfall. Since soil moisture does not vary much diurnally, daily samples were output. Data were downloaded to a laptop computer during two or three annual site maintenance visits.

2.5 Analysis

Analysis focused on growing-season microclimate conditions at the blocks. In order to standardize comparisons among different years and blocks, the growing season was defined as the period from 1 May to 30 September for the purposes of calculating soil temperature index (STI), mean soil temperature, and mean minimum air temperature. For the purpose of looking at the frequency and severity of summer frost events, it was decided to use the period of 1 June–15 August, when the current year's growth on seedlings is most sensitive to frost damage, rather than the entire growing season.

Soil temperature index is calculated in the same way as growing degree days. The STI for a particular day would be the total degrees that the daily average soil temperature exceeds a threshold temperature. For example, if a 5°C threshold was set, and the daily average temperature was 7°C, then the STI equals 2 for the day. The temperature threshold used in this analysis was 5°C. The name STI has been used here to avoid the assumption that the index is related to seedling growth and phenology. The STI integrates such factors as solar irradiance, near-ground air temperature, snow-free season, and soil physical properties. These factors may affect seedling growth and survival; however, no growth effect should be inferred based on the STI alone.

Soil water stress was defined to be occurring when the soil water potential at a depth of 15 cm was less than -1.0 MPa. Previous research has found “permanent wilting points” for many plants to range between -1.0 and -5.0 MPa, with the often quoted value for field crops being -1.5 MPa (Richards and Wadleigh 1952). In this study, a day when soil water potential was measured at less than -1.0 MPa was identified as a soil water stress day. The number of these days was totalled for each growing season and site.

The snow-free date was determined for each year and site by observing daily minimum and maximum 1-cm soil temperature. The 1-cm soil temperature sensors are close enough to the bottom of the snowpack that daily minimum and maximum temperatures measure very close to 0°C during the snowmelt period, when the soil is being flushed with snowmelt water. Snowmelt finished when the daily maximum 1-cm soil temperature first rose above 0.5°C. In some cases, snow cover was temporarily re-established by late snowfalls for a few days.

Soil freezing can potentially interfere with root function or it can damage roots and reduce their ability to take up water, which leads to winter desiccation of the needles. To measure the prevalence of soil freezing, the total number of days, per winter season, when the 15-cm soil temperature dropped below -2°C (soil freeze days) were determined.

3 RESULTS AND DISCUSSION

3.1 Soil Temperature

Mean accumulated 5°C soil temperature index (STI) at each block, treatment, and microsite are shown in Table 2 (see Appendix 1 for full dataset). Clearcuts accumulated 25–35% more STI than the warmest partial cut microsite, which was always the north edge locations. When compared with the average over all three partial cut microsites, the clearcuts accumulated 38–49% more STI. The microsites measured at the south edges of the gaps in the partial cuts had the lowest seasonal totals of STI in every case. These trends can be explained by larger solar input to the soil surface in the clearcuts and north edge locations, given similar surface compositions. These results are consistent with those for clearcuts and partial cuts in the Engelmann Spruce–Subalpine fir forests northeast of Likely, B.C., where STI accumulation was much higher in clearcuts than in 20 m diameter openings (Stathers et al. 2001). The growing-season STI totals decreased with increasing elevation, as evidenced by the clearcut values of 759, 748, and 581 for blocks 1, 3, and 5, respectively. This was most likely caused by later snow-free dates at the higher-elevation sites, causing a delay in soil warming; however, lower mean air temperatures, wetter soils, and greater cloud cover as elevation increases may also contribute to lower STIs.

TABLE 2 *Mean (standard deviation in parentheses) growing-season (1 May–30 September) 5°C STI, based on daily average 15-cm soil temperature, for the period 1999–2003*

	North edge	Centre	South edge
Block 1			
Clearcut	–	759 (132)	–
Partial cut	609 (23)	599 (24)	441 (28)
Block 3			
Clearcut	–	748 (102)	–
Partial cut	554 (32)	510 (29)	456 (23)
Block 5			
Clearcut	–	581 (59)	–
Partial cut	436 (28)	409 (46)	326 (31)

Table 3 shows mean growing-season 15-cm soil temperatures, while annual data for each growing season and station are reported in Appendix 2. Mean growing-season soil temperatures ranged from 9.7°C at the block 1 clearcut to 5.9°C at the south edge of the block 5 partial cut. This pattern is similar to that observed by Sagar et al. (2001), who also found soil temperature to be warmest in a clearcut, followed by north edge microsites, with south edge microsites being the coldest. Figure 3 shows representative plots of soil temperature from the 2001 growing season for all blocks, treatments, and microsites. Soil temperatures reached their peak by mid-August and began a steady decline thereafter. Soil temperatures were below 10°C for much of the growing season at the south edge microsites on all blocks, and at all microsites in the block 5 partial cut.

Figure 4 shows the differences in daily average 15-cm soil temperatures at the three partial cut microsites from the block mean (mean of the daily average temperature of the three microsites) in 2001. This year shows a typical pattern. South edge microsites started out the season up to 2°C colder because the later snowmelt delayed warming. Despite some fluctuations, the overall trend shows that north edges were warmest, followed by centre microsites, and finally south edges. The fluctuations in the patterns, although similar from year to year in a given block, were likely caused by the irregular shape of the gaps, which leads to different patterns of sun and shade throughout the season. Differences among the microsites diminished in the winter, when solar loading was much less of a factor.

TABLE 3 *Mean (standard deviation in parentheses) growing-season 15-cm soil temperature (°C) for the period 1999–2003*

	North edge	Centre	South edge
Block 1			
Clearcut	–	9.7 (0.9)	–
Partial cut	8.6 (0.2)	8.4 (0.2)	7.2 (0.2)
Block 3			
Clearcut	–	9.2 (0.4)	–
Partial cut	8.0 (0.2)	7.7 (0.3)	7.2 (0.2)
Block 5			
Clearcut	–	8.1 (0.4)	–
Partial cut	7.1 (0.3)	6.8 (0.4)	5.9 (0.2)

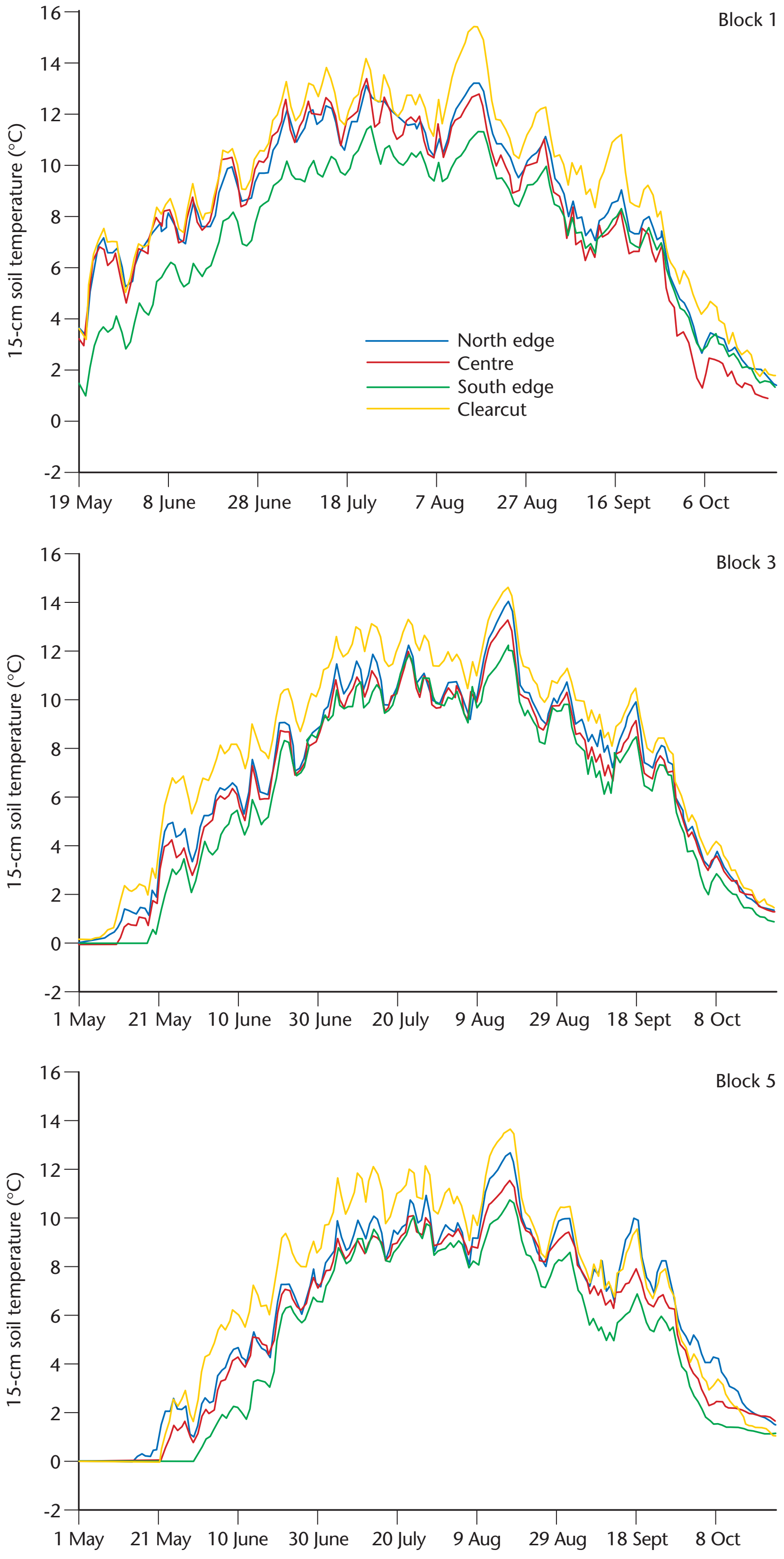

FIGURE 3 *Example growing season (2001) showing plots comparing daily average 15-cm soil temperatures in the clearcuts with those in the partial cut microsites for each block.*

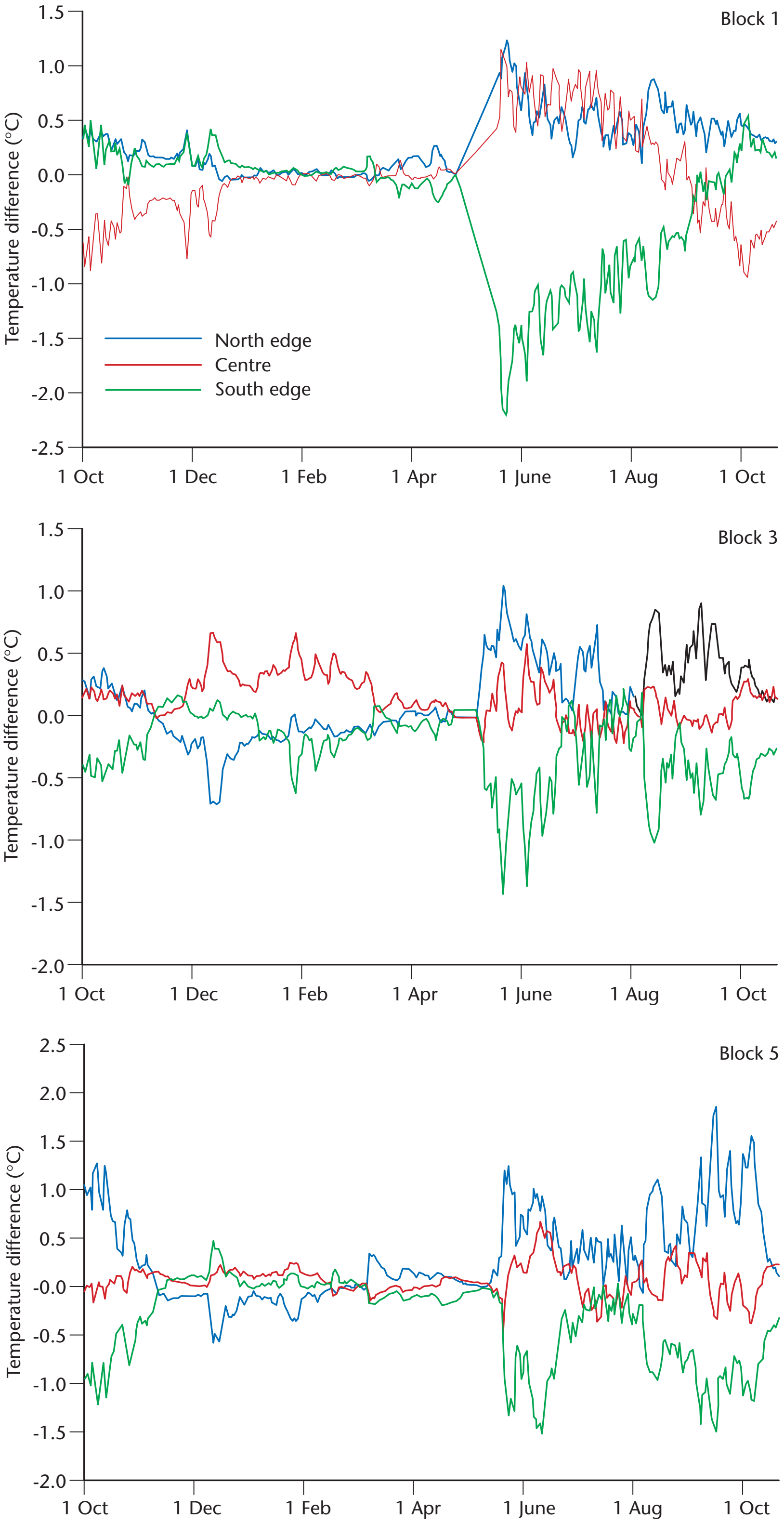

FIGURE 4 *Example year showing differences among daily average 15-cm soil temperature at the partial cut treatments for each block over the period October 2000–October 2001. Differences were calculated by taking the mean of daily averages over the three microsites, and subtracting this from the average temperatures measured at each position.*

In Figure 5, the daily mean 15-cm soil temperatures at the block 1 clearcut are compared for two different winters. The winter of 1998–99 was a heavy-snow winter, while the snowpack was much shallower during the winter of 2002–03. Although no snow cover data are available for the Satah Mountain area, the automated snowpillow data for Upper Mosley Creek (B.C. Ministry of Sustainable Resource Management; wlapwww.gov.bc.ca/rfc/archive) about 80 km south of Satah Mountain, showed a peak snow water equivalent of 410 mm for 1998–99 and 215 mm for 2002–03. During the heavy-snow winter, soil temperature never declined much below the freezing point due to the insulating effect of the snowpack. This pattern is typical of high-elevation and other sites that consistently have deep snowpacks. In contrast, there was long lasting and deep soil freezing at 15 cm during the light-snow winter. Figure 6 shows the annual average number of soil freeze days (soil temperature <-2°C) for all blocks, treatments and microsites, and Appendix 3 contains the annual data for each station. Soil freeze days declined markedly as elevation, and thus winter snowpack, increased. There was also a trend towards more soil freeze days in the clearcuts compared to the partial cuts. This may have resulted from lower night air temperatures, and, at certain points during the winter, snow depths could have been lower due to wind and sun in the clearcut. There was no consistent trend of differences in soil freeze days among the three partial cut microsites for blocks 1, 3, and 5.

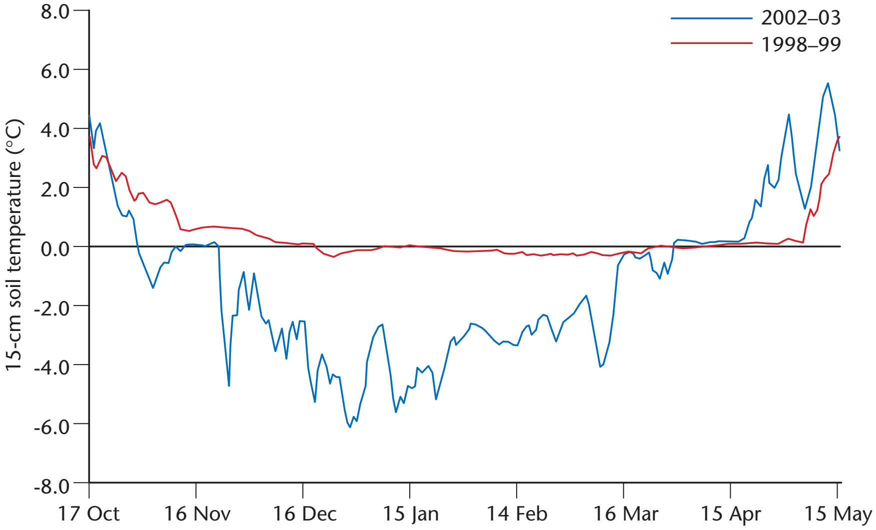

FIGURE 5 *Comparison of daily average 15-cm soil temperatures at the block 1 clearcut for a heavy- (1998–99) and a light- (2002–03) snow winter.*

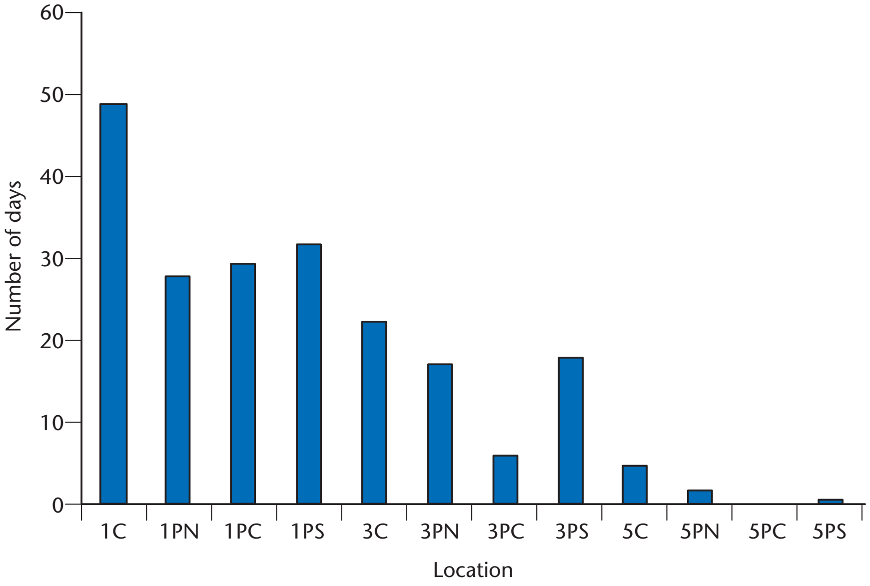

FIGURE 6 *Mean number of days per winter when the average 15-cm soil temperature is less than -2°C (1997–2003). Key to locations is as follows: 1C = block 1 clearcut; 1PN = block 1 partial cut, north edge; 1PC = block 1 partial cut, centre; 1PS = block 1 partial cut, south edge; 3C = block 3 clearcut; 3PN = block 3 partial cut, north edge; 3PC = block 3 partial cut, centre; 3PS = block 3 partial cut, south edge; 5C = block 5 clearcut; 5PN = block 5 partial cut, north edge; 5PC = block 5 partial cut, centre; 5PS = block 5 partial cut, south edge.*

3.2 Air Temperature

Figure 7 shows the daily minimum 15-cm air temperature for the clearcut and partial cut (north edge location) of block 1, during the 2002 growing season. It can be readily seen that frosts were frequent and severe, especially in the clearcut, where the temperature dropped below -10°C once in June and July. This general pattern was repeated from year to year (Appendix 4). The mean daily minimum 15-cm air temperatures for the growing seasons are reported in Table 4. Means ranged from 0.5 to -1.5°C for the partial cuts and from -1.6 to -2.5°C for the clearcuts. To put these temperatures in perspective, in the Sub-Boreal Spruce Dry, Warm biogeoclimatic subzone (near Gavin Lake, B.C.) the mean minimum temperature for a uniform shelterwood (15 m^2/ha retained basal area) was approximately 4°C during the 2003 growing season (R. Sagar, unpublished data, 2003, B.C. Ministry of Forests, Williams Lake, B.C.).

Figure 8 shows the differences in daily minimum 15-cm air temperatures at the three partial cut microsites from the block mean (mean of the daily average temperature of the three microsites) for the 2001 growing season. The patterns shown in Figure 8 are typical for other years. The extreme temperature differences between the warmest and coldest microsites were on the order of 1–2°C. For two of the three blocks, the centre microsite was the coldest, while the north edge microsites were the warmest at all three blocks. The differences among the microsites can be explained in part by the sheltering effect of the surrounding forest and the effect of soil temperature on air temperature. Temperature sensors further away from the forest edge (i.e., centre microsite) have a larger sky view factor and thus receive less long-wave radiation from above, making them cooler than sensors with a small sky view factor (i.e., north and south edge microsites). The soil surface can affect nighttime air

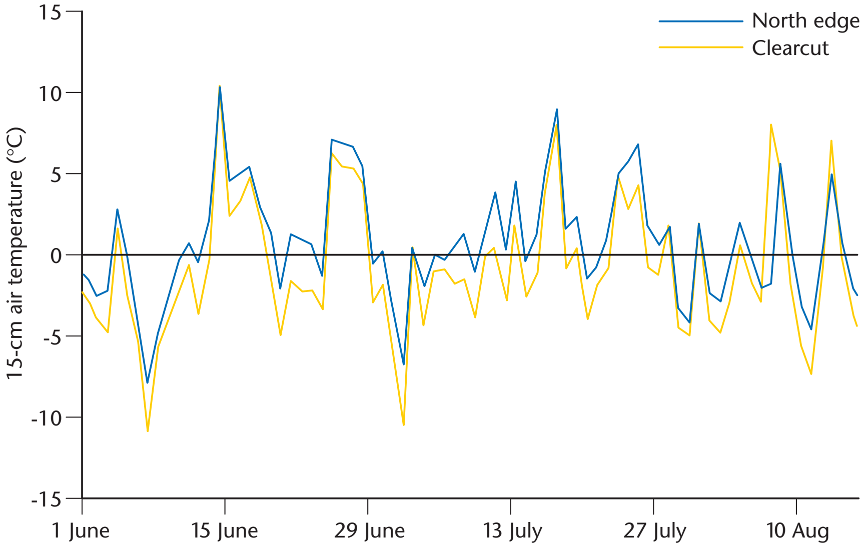

FIGURE 7 *Comparison of daily minimum 15 cm air temperature at the clearcut and north edge microsites for block 1 during the 2002 growing season.*

TABLE 4 *Mean (standard deviation in parentheses) growing-season minimum 15-cm air temperature (°C) for the period 1999–2003*

		North edge	Centre	South edge
Block 1				
	Clearcut	–	2.5 (0.2)	–
	Partial cut	0.9 (0.2)	-1.5(0.3)	-0.9 (0.3)
Block 3				
	Clearcut	–	-1.6 (0.5)	–
	Partial cut	0.5(0.2)	0.1 (0.3)	-0.4 (0.3)
Block 5				
	Clearcut	–	-2.0 (0.8)	–
	Partial cut	0.0 (0.3)	-0.1 (0.4)	0.3 (0.3)

temperature by transferring varying amounts of radiant and sensible heat to the sensor. For example, warmer daytime soil temperatures (and sensors) can lead to warmer nighttime sensor temperatures. The effect of soil temperature on nighttime air temperatures is also determined in part by the soil surface type (i.e., the organic layer depth and composition). A deep organic layer inhibits the transfer of heat to the mineral soil below due to its low thermal conductivity and tends to be very warm at the air–organic interface during the day. At night, this heat is given up very quickly, leaving little to be given off later in the night. The effect of opening sizes and position within openings on minimum air temperature is discussed in some detail by Groot and Carlson (1996).

The seasonal (1 June–15 August) mean number of frost events is shown in Table 5 and the full dataset for each year and station is reported in Appendix 5. Frost (air temperature <0°C) occurred on more than 50% of the nights at the block 1 and 5 clearcuts. In fact, the frequency was almost two out of every

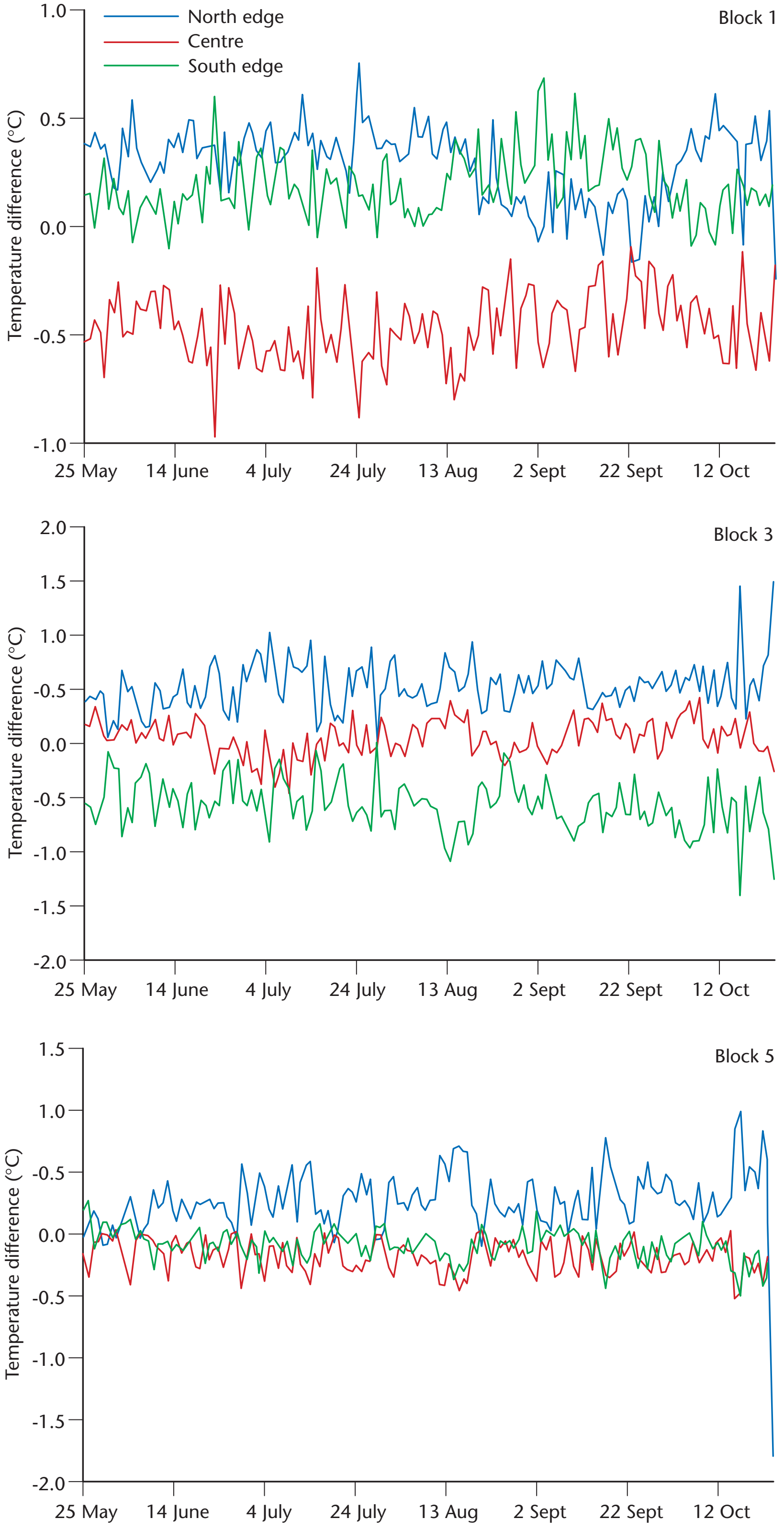

FIGURE 8 *Differences among daily minimum 15-cm air temperature at the partial cut treatments for each block over the period October 2000–October 2001. Differences were calculated by taking the mean of daily minimums over the three microsites, and subtracting this from the minimum temperatures measured at each position.*

TABLE 5 *Mean (standard deviation in parentheses) number of frost events (based on daily minimum 15 cm air temperature) determined using the 76-day period, 1 June–August 15, each year from 1999 to 2003*

	Number of days minimum 15 cm T_a < 0°C			**Number of days minimum 15 cm T_a < -4°C**		
	North edge	**Centre**	**South edge**	**North edge**	**Centre**	**South edge**
Block 1						
Clearcut	–	43 (6)	–	–	12 (4)	–
Partial cut	26 (4)	34 (8)	29 (6)	4 (2)	5 (2)	4 (2)
Block 3						
Clearcut	–	36 (7)	–	–	7 (2)	–
Partial cut	20 (3)	22 (4)	28 (5)	2 (1)	2 (1)	4 (3)
Block 5						
Clearcut	–	49 (10)	–	–	14 (4)	–
Partial cut	24 (6)	29 (5)	27 (6)	3 (2)	3 (2)	3 (2)

three nights at the block 5 clearcut. Frost occurred on an average of 17 nights during July at the block 5 clearcut, with five of these being severe frost events (air temperature <-4°C). Although there were fewer frosts in the partial cuts, they still occurred frequently. Severe frosts occurred, on average, at least twice every season at all locations, and as many as 14 times at the block 5 clearcut.

Low air temperature has been shown to cause significant photosynthesis reductions in Engelmann spruce (*Picea engelmannii*) after exposure to temperatures of -4°C or lower (Delucia and Smith 1987). This suggests that, apart from the obvious problem of frost killing new growth, severe frost in the summer may limit productivity of interior spruce (*Picea glauca* x *P. engelmannii*) planted on these sites. The partially cut treatments significantly reduced the incidence of severe frost compared to the clearcuts (see Figure 9). Severe frosts were uncommon during the month of July at all partially cut

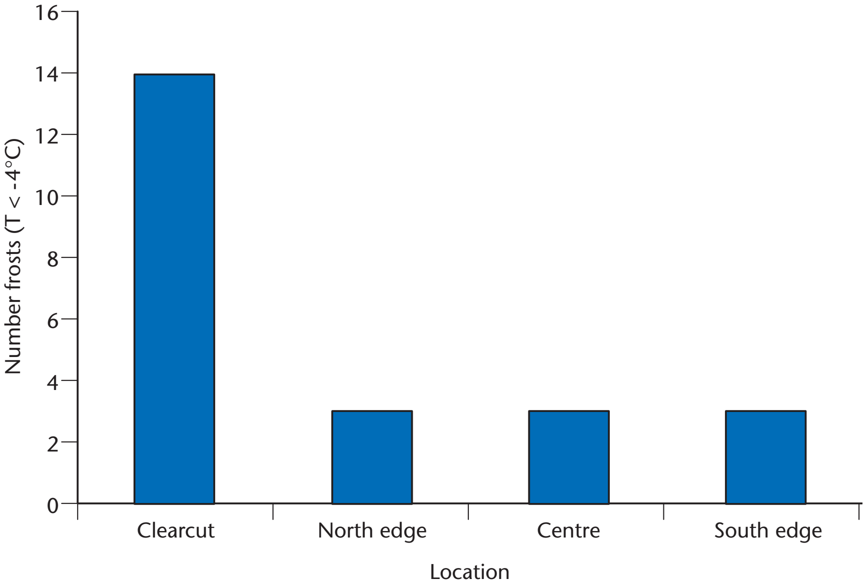

FIGURE 9 *Total number of severe frosts (based on daily minimum 15-cm air temperatures <-4°C) at block 5, for the period 1 June–15 August during the 2002 growing season.*

microsites (zero or one occurrence), while they occurred in most years at the clearcut treatments (Appendix 5). Another benefit of partial cutting, with respect to frost damage, is the reduction of direct solar irradiance due to shading by retained canopy, which may limit the severity of physiological damage after a heavy frost (Dang et al. 1992). The lessening of severe frosts and reduction in solar radiation may explain the observed trends in spruce seedling survival and frost damage on blocks 1 and 5 (Daintith et al. 2005). For instance, 5 years after planting, in block 1, spruce seedling survival was 78% in the clearcut compared to 92% in the irregular group shelterwood (whole tree harvesting) treatment; while in block 5, survival was 35% in the clearcut and 89% in the shelterwood. Survival was similar (>95%) for both treatments in block 3, where the average number of severe frost events was about half of that in the other two blocks. In the main research trial, across all five blocks, the amount of frost damage to terminal buds was 37% in the clearcuts, but only 18% in the shelterwood (whole tree) treatments.

3.3 Precipitation and Soil Moisture

Table 6 displays seasonal totals of rainfall in the clearcut treatments. The most reliable record was at block 1, and it indicates that 2000 and 2001 had wetter growing seasons than 2002 and 2003. There was also an indication that rainfall increased with elevation, as expected.

Figure 10 details the mean number of growing-season soil water stress days (soil water potential <-1.0 MPa). No growing-season water stress was observed in the clearcut or north edge of the partial cut at block 5. This is probably due to heavier and later melting winter snowpacks, higher summer rainfall, and lower evaporative loss (due to lower mean air temperatures). More stress days were observed at block 3 than at block 1. This difference could be due to regeneration density, as there was a higher density of tree regeneration on block 3 than block 1 (37% higher on the partial cut and 400% higher on the clearcut) (Steen et al. 2005).

Generally, more stress days were observed at the north edge of the openings in the partial cut than in the clearcuts. This may be a result of higher evapotranspiration rates, mainly from the adjacent forest in the partial cuts; but it is difficult to generalize, as we did not collect any soil water data for the other microsites within the partial cuts. Figure 11 shows a plot of growing-season soil water potential that illustrates a typical pattern for soil water potential in most years. Within the study area, water stress days typically occurred in one or two discrete periods during the late summer of each data collection year (R. Sagar, unpublished data, B.C. Ministry of Forests, Williams Lake, B.C.). It is important to note that the convention is to describe soil water potential as a negative number, hence values become increasingly negative as the soil dries.

TABLE 6 *Total growing-season rainfall (mm) at each block for the years 2000–2003*

Year	Block 1	Block 3	Block 5	Measurement period
2000	163.1	–	–	3 June–13 September
2001	172.7	–	71.1[a]	19 May–21 October
2002	77.2	115.8	133.3	14 June–16 October
2003	105.9[b]	96.8	112.2[b]	31 May–6 October

[a] Block 5, 2001 – Total rainfall for the period 7 August–21 October (new funnel was installed on 7 August).

[b] Blocks 3 and 5, 2003 – rain gauges found to be significantly out of level on 15 August 2003 site visits.

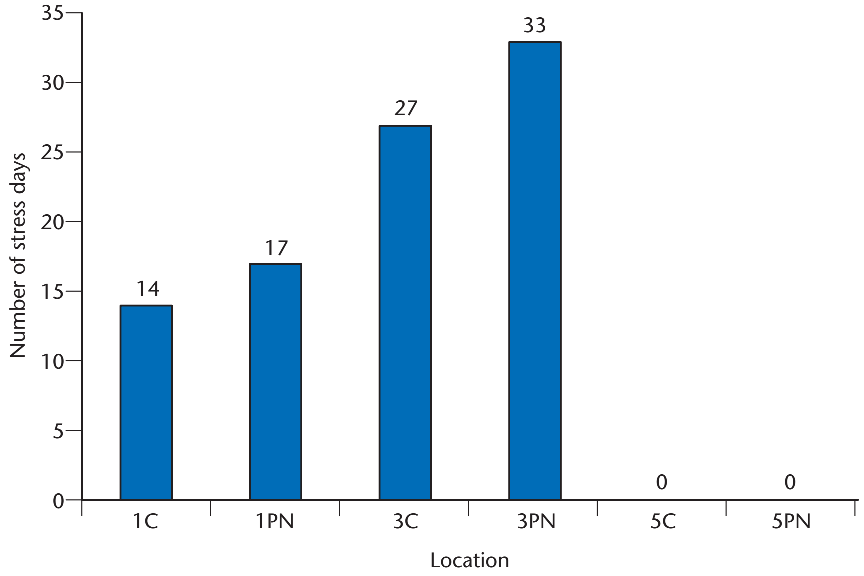

FIGURE 10 *Mean annual number of soil water stress days (days when the 15-cm soil water potential is less than -1.0 MPa bar) for each block and treatment (1999–2003). Note that the soil water potential was measured only at the north edge locations of the partial cuts. See Figure 6 for key to location terms.*

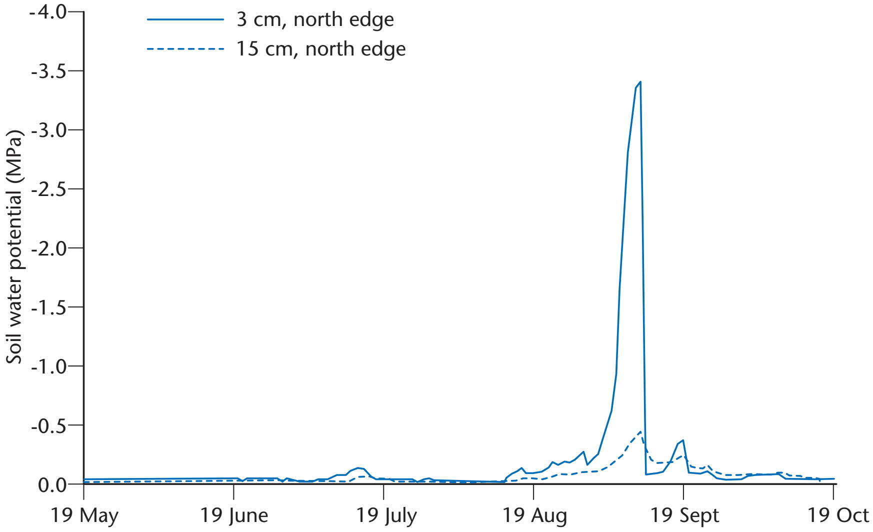

FIGURE 11 *Growing-season soil water potential at the block 1 partial cut during 2001. Measurements were made at depths of 3 and 15 cm beneath the mineral soil–organic layer interface.*

At this particular site, soil water stress measured at 3 cm soil depth began in early September and lasted about a week until a rainfall wet the soil. Soil water potential, measured at a soil depth of 15 cm, decreased over the same time period, but not as much as at the 3 cm depth. Annual growing-season soil water stress days are reported for all blocks, treatments, and microsites in Appendix 6.

3.4 Snow-free Dates

The mean snow-free dates for all blocks, treatments, and microsites are given in Table 7 and the full dataset for each year and station are in Appendix 7. The effect of elevation is clear. The snow-free date averaged 1 month later at the block 5 clearcut than the block 1 clearcut. The reasons are heavier snowpacks and slower melting due to lower average air temperatures at higher elevations. Clearcuts generally were snow-free a few days earlier than the earliest-melting partial cut site (except at block 5). South edge microsites were the latest to be snow-free in two of the three partial cuts.

TABLE 7 *Mean snow-free date (based on 1-cm soil temperatures) for each block, treatment, and microsite from 1998 to 2003*

	North edge	Centre	South edge
Block 1			
Clearcut	–	17 Apr	–
Partial cut	20 Apr	29 Apr	26 Apr
Block 3			
Clearcut	–	26 Apr	–
Partial cut	30 Apr	3 May	8 May
Block 5			
Clearcut	–	17 May	–
Partial cut	6 May	16 May	26 May

4 SUMMARY

Soil temperatures were significantly warmer in the clearcut treatments in comparison to partial cuts. This manifests itself in a higher STI total in the clearcuts (37–48% more). The main reason that soil temperature and STI were higher in the clearcuts was higher total solar irradiance in the clearcuts. Earlier snow-free dates in the clearcuts also increase STI accumulation. Winter soil freezing was reduced in the partial cut treatments due to less extreme minimum air temperatures and longer duration of snow cover. The overall number of frosts (air temperature <0°C) and severe frosts (air temperature <-4°C) was significantly less in the partial cut treatments compared to the clearcuts. This is largely due to the sheltering effect of the surrounding forest.

The differences in microclimate among microsites within the partial cuts were less pronounced than the overall differences between clearcuts and partial cuts. Soil temperature and STI accumulation were greatest at the north edge microsites, and least at the south edges. Centre locations generally had more frost events than edge microsites due to increased sky view factors. Snow-free dates were 1–3 weeks later at the south edge microsites in comparison to the north edges. Assuming that water is not limiting, the north edge microsite should be the most favourable location for seedling growth in a partial cut due to the earlier snow-free dates, higher soil temperature, increased solar irradiance, and good frost protection. The centre microsite would be the next best if frost damage is not too limiting. The south edge site is limited by low solar irradiance, cooler soil temperatures, and later snow-free dates that decrease the length of the growing season. These results are similar to the findings at other high-elevation study sites in the interior of British Columbia (Sagar et al. 2001; Stathers et al. 2001; and Spittlehouse et al. 2004). Sagar et al. (2001) reported that mean growing-season 10-cm soil temperatures were more than 2°C warmer at the north edge location when compared to the south edge. It is interesting to note that, given the relationship between solar loading and soil temperature, microsites with the lowest soil temperatures at a given block also receive the lowest solar irradiance. This circumstance may make these sites less favourable for regeneration of seedlings, especially pine, than sunnier microsites within the same opening.

As expected, soil temperature and STI decreased with increasing elevation (moving from block 1 to block 5). However, the effect of elevation was less important as a determinant to the total number of growing-season frosts. Block 1 had a similar number of frosts to block 5, with block 3 having the fewest. Block 1 also had the lowest extreme minimum summer air temperatures recorded (see Appendix 4). Soil freezing decreased markedly with increased elevation due to heavier and longer-lasting snowpacks. The number of soil moisture stress days was minimal at block 5, which had higher annual precipitation. Overall, the effect of increasing elevation on microclimate was similar to that in moving from the north edge (most favourable) to the south edge (least favourable) within an opening.

The Cariboo – Chilcotin Land Use Plan (CCLUP) (Government of B.C. 1995) set aside 181 000 ha to be harvested with “modified” harvesting systems to maintain forage throughout the wintering area of northern caribou. The microclimate in small gaps is different from that of clearcuts, and, therefore, could influence the survival and growth of lichen and regeneration, as well as the abundance of mushrooms. The influence may be direct or indirect. For example, in the planted stock study on the trial area (Daintith et al. 2005), regeneration, particularly spruce, showed more evidence of frost damage in the clearcuts where the number of frost events was greatest. In the same study, the diameter growth of pine was significantly ($\alpha = 0.05$) less in the partial cuts (6.8–7.9 mm) than the clearcuts (10.5 mm); this may be attributable partially to lower soil temperature, but other factors such as light (not measured directly) are also important. This suggests using larger opening sizes to improve growth, but at the risk of increased frost.

Initial results from the pilot study (Miège et al. 2001) show that the small openings (15 m diameter) in the group selection silvicultural system had similar amounts of lichen compared to uncut forests, whereas the clearcuts with reserves had substantially less lichen. The authors point out that when the forest canopy is suddenly removed, the lichens are exposed to direct solar radiation, to which they can not quickly adapt, so they dry out and die. Although light wasn’t directly measured in the microclimate study, the higher soil temperatures do indicate more solar radiation in the clearcuts. The response of the common terrestrial lichen species and commercial mushroom species are the subjects of ongoing studies (Waterhouse 1998).

Evidence to date suggests that using group selection or irregular group shelterwood would meet the objective of maintaining caribou habitat while allowing some timber harvesting.

APPENDIX 1 Growing-season (1 May–30 September) total 5°C soil temperature index (STI) based on 15-cm soil temperatures for each block, treatment, and microsite for 1997–2003. Means and standard deviations are based on the period 1999–2003.

	Block 1				Block 3				Block 5			
Year	Clearcut	Partial cut North edge	Partial cut Centre	Partial cut South edge	Clearcut	Partial cut North edge	Partial cut Centre	Partial cut South edge	Clearcut	Partial cut North edge	Partial cut Centre	Partial cut South edge
1997	661	637	515	483	671	542	400	429	–	–	–	–
1998	943	839	874	677	942	483	454	389	–	590	524	478
1999	663	608	612	470	687	559	530	464	562	427	445	351
2000	699	636	613	461	706	545	520	463	562	431	382	318
2001	686	594	573	426	657	503	460	416	502	397	341	278
2002	760	580	572	401	725	575	517	474	648	463	438	356
2003	987	629	622	445	773	587	525	462	632	463	438	326
Mean	**759**	**609**	**599**	**441**	**748**	**554**	**510**	**456**	**581**	**436**	**409**	**326**
S.D.	132	23	24	28	102	32	29	23	59	28	46	31

Shaded cells not used in calculations of mean and standard deviation (S.D.); see notes below

1 2003 block 3 partial cut, north edge – sensor failed on 4 June so no data (STI value was estimated by regression with centre position)

2 2001 block 1 partial cut, north, south, and centre – missing data 27 April through 18 May based on data from clearcut, no STI were lost

3 2000 block 1 partial cut – bad data 30 April through 2 June (missing STI was estimated based on years with complete data)

4 1999 block 1 clearcut – missing data 17–27 September (probably no more than 25 missing STI)

5 1998 block 3 partial cut – missing data from 8 August through 3 November

6 1998 block 5, partial cut – data collection began 28 May (i.e., no data 1–27 May); estimated missing STI : north edge and centre <10; south edge 0

7 1997 blocks 1 and 3 – monitoring began on 5 June (i.e., no data 1 May –June)

8 1997 blocks 1 and 3 partial cuts – no data for centre position from 5 June to 1 July

APPENDIX 2 Growing-season (1 May–30 September) mean daily 15 cm soil temperatures and mean daily minimum 15-cm air temperatures (°C) for each block, treatment, and microsite for 1997–2003. Means and standard deviations are for the period 1999–2003.

	Block 1				Block 3				Block 5			
Season	Clearcut	Partial cut North edge	Partial cut Centre	Partial cut South edge	Clearcut	Partial cut North edge	Partial cut Centre	Partial cut South edge	Clearcut	Partial cut North edge	Partial cut Centre	Partial cut South edge
Mean 15-cm soil temperature												
1997	10.6	10.4	10.7	9.1	10.7	9.6	9.4	8.6	–			
1998	11.1	10.5	10.6	9.1	11.0	9.6	9.1	8.1	–	9.7	9.2	8.8
1999	9.1	8.6	8.5	7.4	9.0	8.1	8.0	7.2	7.9	7.2	7.2	6.1
2000	9.3	8.7	8.5	7.4	9.3	8.1	7.9	7.3	8.1	7.3	6.8	5.9
2001	9.1	8.5	8.2	7.2	8.5	7.7	7.3	6.9	7.4	6.6	6.1	5.5
2002	9.6	8.4	8.3	6.8	9.3	8.2	7.7	7.2	8.4	7.3	7.1	6.1
2003	11.3	8.8	8.7	7.3	9.7	_	7.8	7.3	8.5	7.2	7.0	5.9
Mean	**9.7**	**8.6**	**8.4**	**7.2**	**9.2**	**8.0**	**7.7**	**7.2**	**8.1**	**7.1**	**6.8**	**5.9**
S.D.	0.9	0.2	0.2	0.2	0.4	0.2	0.3	0.2	0.4	0.3	0.4	0.2
Mean daily minimum 15 cm air temperature												
1997	1.5	0.0	0.0	0.5	0.3	1.8	1.9	0.7	–			
1998	-0.3	1.1	1.0	1.6	1.2	3.3	3.1	2.2	–	2.7	2.2	2.1
1999	-2.2	-1.1	-1.1	-0.6	-0.9	0.6	0.3	0.0	-1.0	0.0	0.3	0.3
2000	-2.5	-0.7	-1.3	-0.6	-1.2	0.7	0.3	-0.4	-1.5	0.1	-0.1	0.3
2001	-2.5	-0.8	-1.5	-0.9	-1.7	0.2	-0.3	-0.7	-2.8	-0.5	-0.7	-0.1
2002	-2.7	-1.0	-1.6	-1.1	-1.8	0.4	-0.1	-0.4	-1.9	0.0	0.0	0.4
2003	-2.5	-1.0	-1.9	-1.1	-2.2	0.5	0.1	-0.7	-2.6	0.3	-0.1	0.6
Mean	**-2.5**	**-0.9**	**-1.5**	**-0.9**	**-1.6**	**0.5**	**0.1**	**-0.4**	**-2.0**	**0.0**	**-0.1**	**0.3**
S.D.	0.2	0.2	0.3	0.3	0.5	0.2	0.3	0.3	0.8	0.3	0.4	0.3

Shaded cells not used in calculations of mean and standard deviation (S.D.); see notes below

1 2003 block 3 partial cut, north edge – sensor failed on 4 June so no data
2 2001 block 1 partial cut, north, south ,and centre – missing data 27 April–18 May (corrected for missing data using linear regression)
3 2000 block 1 partial cut – bad data 30 April–2 June (corrected for missing data using linear regression)
4 1999 block 1 clearcut – missing data 17–27 September
5 1998 block 3 partial cut – missing data from 8 August through 3 November
6 1998 block 5 partial cut – data collection began 28 May (i.e., no data 1–27 May)
7 1997 blocks 1 and 3 – monitoring began on 5 June (i.e., no data 1 May–4 Jun)
8 1997 blocks 1 and 3 partial cuts – no data for centre position from 5 June to 1 July

APPENDIX 3 Seasonal (September–May) total days when daily average 15-cm soil temperatures were less than -2°C for each block, treatment, and microsite for 1997–2003. Also reported are the extreme minimum, daily average soil temperatures for each season.

	Block 1				Block 3				Block 5			
Season	Clearcut	Partial cut North edge	Partial cut Centre	Partial cut South edge	Clearcut	Partial cut North edge	Partial cut Centre	Partial cut South edge	Clearcut	Partial cut North edge	Partial cut Centre	Partial cut South edge
1997–98	21	12	9	17	4	7	2	13	–	–	–	–
1998–99	0	0	0	0	0	0	0	0	0	0	0	0
1999–00	17	0	0	0	0	0	0	0	0	0	0	0
2000–01	54	10	12	10	36	13	2	17	0	0	0	0
2001–02	95	48	52	61	9	24	0	0	0	0	0	0
2002–03	105	96	102	101	85	58	31	78	23	8	0	2
Mean	**49**	**28**	**29**	**32**	**22**	**17**	**6**	**18**	**5**	**2**	**0**	**0**
S.D.	44	38	41	41	34	22	12	30	10	4	0	1
Extreme minimum, daily average soil temperature												
1997–98	-3.4	-3.4	-3.3	-3.4	-2.5	-2.8	-2.2	-3.3	–	–	–	–
1998–99	-0.4	-0.2	-0.3	-0.2	-0.1	-0.3	0.0	-0.1	0.2	0.2	0.2	0.1
1999–00	-2.3	-1.6	-1.8	-1.7	-0.9	-1.5	-0.9	-1.3	-0.2	-0.3	-0.3	-0.4
2000–01	-5.0	-2.8	-3.3	-2.5	-3.1	-3.3	-2.0	-2.9	-0.8	-1.8	-1.0	-0.9
2001–02	-4.2	-3.3	-3.3	-3.9	-2.4	-2.8	-1.7	-1.9	-0.2	-0.5	-0.2	-0.3
2002–03	-6.2	-4.6	-5.1	-4.9	-4.3	-3.8	-3.1	-4.5	-3.0	-2.3	-1.6	-2.0

Note: Correction was applied to soil temperatures if offset was >0.1°C

S.D. = standard deviation

1997–98 block 1 partial cut, centre – offset not applied because it appeared late in the winter

APPENDIX 4 Extreme daily minimum 15-cm air temperatures (°C) determined for the period 1 June–15 August, and for July only of each year, at each block, treatment, and microsite for 1997–2003.

Block 1

	Clearcut		Partial cut North edge		Partial cut Centre		Partial cut South edge	
Year	**Season**	**July**	**Season**	**July**	**Season**	**July**	**Season**	**July**
1997	-8.4	-6.3	-6.0	-3.9	-5.0	-4.1	-5.8	-3.6
1998	-8.0	-8.0	-5.0	-4.2	-5.4	-4.4	-5.0	-4.1
1999	-12.4	-6.0	-8.8	-3.1	-9.0	-3.3	-8.5	-3.0
2000	-8.2	-3.8	-4.7	-1.8	-5.6	-2.3	-5.0	-1.8
2001	-8.5	-6.4	-5.6	-3.2	-6.3	-4.0	-6.1	-3.2
2002	-10.9	-10.5	-8.0	-6.8	-8.9	-7.6	-7.8	-7.0
2003	-9.3	-4.0	-6.5	-2.9	-8.0	-3.5	-7.0	-2.6
Extreme	**-12.4**	**-10.5**	**-8.8**	**-6.8**	**-9.0**	**-7.6**	**-8.5**	**-7.0**

Block 3

	Clearcut		Partial cut North edge		Partial cut Centre		Partial cut South edge	
Year	**Season**	**July**	**Season**	**July**	**Season**	**July**	**Season**	**July**
1997	-5.7	-4.2	-4.0	-1.7	-2.3	-1.9	-5.1	-2.7
1998	-5.5	-5.5	-3.3	-3.3	-3.7	-3.7	-4.4	-4.4
1999	-8.0	-4.9	-5.2	-1.8	-5.7	-2.5	-6.4	-3.5
2000	-6.0	-3.0	-3.9	-0.7	-4.4	-1.7	-4.7	-2.0
2001	-8.9	-5.1	-5.6	-3.1	-6.0	-4.0	-6.7	-4.3
2002	-7.8	-7.8	-4.7	-4.5	-5.4	-5.2	-5.8	-4.7
2003	-9.2	-4.4	-5.3	-1.7	-6.2	-1.9	-6.7	-2.2
Extreme	**-9.2**	**-7.8**	**-5.6**	**-4.5**	**-6.2**	**-5.2**	**-6.7**	**-4.7**

Block 5

	Clearcut		Partial cut North edge		Partial cut Centre		Partial cut South edge	
Year	**Season**	**July**	**Season**	**July**	**Season**	**July**	**Season**	**July**
1997	–	–	–	–	–	–	–	–
1998	–	–	-3.6	-3.6	-4.3	-4.3	-4.2	-4.2
1999	-8.0	-8.0	-6.2	-3.2	-6.5	-4.1	-6.7	-4.0
2000	-7.2	-4.5	-3.8	-0.8	-4.7	-1.6	-4.4	-1.5
2001	-8.5	-7.1	-6.1	-4.0	-6.6	-4.7	-6.3	-4.6
2002	-10.4	-4.6	-6.8	-3.4	-7.4	-3.9	-7.1	-3.8
2003	-7.8	-5.6	-5.7	-0.9	-6.9	-1.6	-6.0	-1.2
Extreme	**-10.4**	**-8.0**	**-6.8**	**-4.0**	**-7.4**	**-4.7**	**-7.1**	**-4.6**

Shaded cells have incomplete data for this year and location; see notes below.

1 1997 blocks 1 and 3 – monitoring began on 5 June (i.e., no data 1 May–4 June)
2 1997 blocks 1 and 3 partial cuts – no data for centre position from 5 June to 1 July
3 1998 block 3 partial cut – missing data from 8 August to 3 November
4 2000 block 1 partial cut – bad data 30 April–2 June

APPENDIX 5 Total frost events (based on daily minimum 15-cm air temperature) (temperature <0°C) and severe frosts (temperature <-4°C) determined for the periods 1 June–15 August, and for July only of each year, at each block, treatment, and microsite for 1997–2003. Means and standard deviations are for the period 1999–2003.

Total frosts (temp <0°C)

Block 1

	Clearcut		Partial cut North edge		Partial cut Centre		Partial cut South edge	
Year	**Season**	**July**	**Season**	**July**	**Season**	**July**	**Season**	**July**
1997	41	15	25	8	12	8	21	6
1998	24	5	12	2	15	3	11	2
1999	40	18	27	10	29	12	24	8
2000	34	11	19	4	23	6	21	4
2001	46	14	27	6	37	10	30	8
2002	51	20	31	10	43	14	37	15
2003	45	16	28	10	39	13	31	10
Mean	**43**	**16**	**26**	**8**	**34**	**11**	**29**	**9**
S.D.	6	3	4	3	8	3	6	4

Block 3

	Clearcut		Partial cut North edge		Partial cut Centre		Partial cut South edge	
Year	**Season**	**July**	**Season**	**July**	**Season**	**July**	**Season**	**July**
1997	26	9	10	2	4	2	22	6
1998	14	3	8	1	9	1	12	2
1999	26	10	18	4	19	4	22	7
2000	30	5	16	1	19	1	25	3
2001	40	13	24	4	28	7	32	8
2002	41	15	23	9	25	10	35	10
2003	42	19	18	7	21	8	27	12
Mean	**36**	**12**	**20**	**5**	**22**	**6**	**28**	**8**
S.D.	7	5	3	3	4	4	5	3

Block 5

	Clearcut		Partial cut North edge		Partial cut Centre		Partial cut South edge	
Year	**Season**	**July**	**Season**	**July**	**Season**	**July**	**Season**	**July**
1997	–	–	–	–	–	–	–	–
1998	–	–	10	3	11	3	11	3
1999	35	14	20	7	22	8	23	9
2000	41	8	25	3	28	4	27	4
2001	56	18	33	7	36	8	37	8
2002	53	21	25	9	30	9	28	8
2003	58	23	16	3	27	11	20	6
Mean	**49**	**17**	**24**	**6**	**29**	**8**	**27**	**7**
S.D.	10	6	6	3	5	3	6	2

APPENDIX 5 *Continued*

Severe frosts (temp <-4°C)

Block 1

	Clearcut		Partial cut North edge		Partial cut Centre		Partial cut South edge	
Year	**Season**	**July**	**Season**	**July**	**Season**	**July**	**Season**	**July**
1997	11	2	6	0	3	1	5	0
1998	6	1	2	1	2	1	2	1
1999	17	6	5	0	5	0	5	0
2000	9	0	2	0	2	0	2	0
2001	10	2	5	0	5	0	5	0
2002	16	5	6	2	7	3	6	2
2003	9	0	3	0	6	0	3	0
Mean	**12**	**3**	**4**	**0**	**5**	**1**	**4**	**0**
S.D.	4	3	2	1	2	1	2	1

Block 3

	Clearcut		Partial cut North edge		Partial cut Centre		Partial cut South edge	
Year	**Season**	**July**	**Season**	**July**	**Season**	**July**	**Season**	**July**
1997	6	1	2	0	0	0	3	0
1998	1	1	0	0	0	0	1	1
1999	5	1	3	0	3	0	3	0
2000	6	0	0	0	1	0	2	0
2001	9	1	2	0	2	0	7	1
2002	9	3	2	1	4	3	7	1
2003	8	2	2	0	2	0	2	0
Mean	**7**	**1**	**2**	**0**	**2**	**1**	**4**	**0**
S.D.	2	1	1	0	1	1	3	1

Block 5

	Clearcut		Partial cut North edge		Partial cut Centre		Partial cut South edge	
Year	**Season**	**July**	**Season**	**July**	**Season**	**July**	**Season**	**July**
1997	–	–	–	–	–	–	–	–
1998	–	–	0	0	1	1	1	1
1999	11	7	3	0	4	1	5	1
2000	11	1	0	0	1	0	1	0
2001	20	5	5	1	6	1	5	1
2002	14	6	3	0	3	0	3	0
2003	15	4	3	0	3	0	3	0
Means	**14**	**5**	**3**	**0**	**3**	**0**	**3**	**0**
S.D.	4	2	2	0	2	1	2	1

Shaded cells indicate incomplete data for period; cells not included in mean and standard deviation (S.D.)

1 1997 blocks 1 and 3 – monitoring began on 5 June (i.e., no data 1 May–4 June)

2 1997 blocks 1 and 3 partial cuts – no data for centre position from 5 June to 1 July

3 1998 block 3 partial cut – missing data from 8 August to 3 November

4 2000 block 1 partial cut – bad data 30 April–2 June

APPENDIX 6 Total number of water stress days (soil water potential <-1.0 MPa) for each block and treatment from 1999 to 2003. Note that the soil water potential was measured at the north edge locations of the partial cuts only.

	Block 1				Block 3				Block 5			
Season	**Clearcut 3 cm**	**Clearcut 15 cm**	**Partial cut North edge 3 cm**	**Partial cut North edge 15 cm**	**Clearcut 3 cm**	**Clearcut 15 cm**	**Partial cut North edge 3 cm**	**Partial cut North edge 15 cm**	**Clearcut 3 cm**	**Clearcut 15 cm**	**Partial cut North edge 3 cm**	**Partial cut North edge 15 cm**
1999	0	0	0	0	0	0	0	0	0	0	0	0
2000	10	0	11	0	0	0	7	0	0	0	0	0
2001	9	0	5	0	12	0	32	10	0	0	0	0
2002	39	45	60	60	87	58	73	_	0	0	0	0
2003	11	25	64	26	120	75	107	123	0	0	0	0
Means	**14**	**14**	**28**	**17**	**44**	**27**	**44**	**33**	**0**	**0**	0	0

1999, all sites – soil moisture monitoring did not begin until 29 June; since it was a wet year, no stress days were missed

APPENDIX 7 Annual snow-free dates based on 1-cm soil temperatures for each site, treatment, and microsite for 1998–2003. Earliest and latest snow-free dates are highlighted.

	Block 1				Block 3				Block 5			
Season	**Clearcut**	**Partial cut North edge**	**Partial cut Centre**	**Partial cut South edge**	**Clearcut**	**Partial cut North edge**	**Partial cut Centre**	**Partial cut South edge**	**Clearcut**	**Partial cut North edge**	**Partial cut Centre**	**Partial cut South edge**
1998	19 Apr	22 Apr	29 Apr	24 Apr	28 Apr	28 Apr	30 Apr	03 May	–	–	–	–
1999	24 Apr	░ 28 Apr	░ 11 May	░ 10 May	░ 30 Apr	░ 07 May	░ 09 May	░ 20 May	░ 23 May	09 May	░ 23 May	░ 31 May
2000	11 Apr	18 Apr	26 Apr	22 Apr	▓ 19 Apr	▓ 22 Apr	▓ 27 Apr	30 Apr	14 May	27 Apr	▓ 11 May	▓ 22 May
2001	░ 25 Apr	–	–	–	28 Apr	04 May	06 May	10 May	17 May	▓ 05 May	14 May	▓ 22 May
2002	17 Apr	20 Apr	29 Apr	28 Apr	28 Apr	░ 07 May	07 May	16 May	22 May	░ 11 May	19 May	29 May
2003	▓ 07 Apr	▓ 14 Apr	▓ 21 Apr	▓ 18 Apr	20 Apr	▓ 22 Apr	30 Apr	▓ 29 Apr	▓ 11 May	09 May	12 May	25 May
Mean	**17 Apr**	**20 Apr**	**29 Apr**	**26 Apr**	**26 Apr**	**30 Apr**	**3 May**	**8 May**	**17 May**	**6 May**	**16 May**	**26 May**

░ = Latest snow-free date

▓ = Earliest snow-free date

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