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Microclimate Studies in Mountain Pine Beetle–Damaged Silvicultural Systems on the Chilcotin Plateau: The Itcha-Ilgachuz Project (1997–2013)

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ABSTRACT

A long-term study on group selection and irregular group shelterwood silvicultural systems began in 1994 to determine their effectiveness in managing habitat for woodland caribou (*Rangifer tarandus caribou*). The systems are being applied in the very dry, cold Sub-Boreal Pine Spruce (SBPSxc) and the very dry, very cold Montane Spruce (MSxv) biogeoclimatic subzones located on the high-elevation Chilcotin Plateau in west-central British Columbia.

Microclimate was monitored in paired partial cut and clearcut treatments in three study blocks over a range of elevations. In these harsh growing environments, partial cutting strongly influenced the air and soil temperature, frost events, and snow-free date. As the microclimate variables changed over the 16-year study period, so did vegetation layers in the partial cuts and clearcuts. In addition, an outbreak of the mountain pine beetle (*Dendroctonus ponderosae*) killed 61% of the mature trees in the partial cut treatments during the middle part of this study (2003–2008) and this mortality and subsequent degeneration of the trees could be affecting the microclimate.

Over the study period, all blocks had frequent and sometimes severe (air temperature $< -4°\mathrm{C}$) frosts throughout the growing season. Partial cuts substantially reduced the number and severity of frosts. In the later portion of the study period, a trend toward decreasing numbers of frosts was noted, as well as decreasing differences among the treatments as the growth of the tree regeneration and other vegetation layers began to shelter the sensor locations. The difference in soil temperature index (STI) between pairs of partial cut and clearcut pairs diminished over time. The year-to-year pattern of accumulated growing season STI was strongly correlated with snow-free date.

The growing season soil moisture regime observed in the clearcut and partial cut openings underwent a major change over the period of this study. In the early years following logging (1997–2003), volumetric soil water content (θ_v) was typically higher in the clearcuts than the partial cut openings. By 2008, θ_v in the clearcuts was often lower than that in the partial cut openings for at least part of the growing season. This has been attributed to the faster growth of regeneration in the clearcuts and the loss of mature trees surrounding the partial cut openings to mountain pine beetle.

Snow-free dates were approximately 2 weeks later at the highest-elevation site in comparison to the lowest site. This lowered soil temperatures and shortened growing seasons at the highest site.

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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. Much of this forest is important habitat for northern caribou, an ecotype of woodland caribou (*Rangifer tarandus caribou*). Under the Cariboo-Chilcotin Land Use Plan (Government of British Columbia 1995), northern caribou are considered a key management species. Federally, under the *Species at Risk Act*, northern caribou are considered threatened, and qualify for protection and recovery.

In winter, caribou prefer mature lodgepole pine forests with high amounts of terrestrial lichen and low snow depths that allow for easy cratering. They also frequent forested areas 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, but this system removes the arboreal lichen and damages terrestrial lichen through physical disturbance, slash loading, loss of substrate, and increased solar radiation (Waterhouse et al. 2011). 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).

The Itcha-Ilgachuz research project on the Chilcotin Plateau in central British Columbia was established in 1994 to test whether silvicultural systems based on partial cutting with extended cutting cycles would reduce the effects of forest harvesting on forage lichens. This study tested a group selection system, based on removal of 33% of the forest every 80 years in small openings (15 m diameter), and two irregular shelterwood treatments (whole-tree and stem-only harvesting methods) in which 50% of the stand area is cut every 70 years in 20–30 m diameter openings. Additional background information on this project can be found in Armleder and Waterhouse (2008), Waterhouse et al. (2010), and Waterhouse et al. (2011).

In addition to maintaining caribou forage species, it is also important that the silvicultural systems are adequately regenerated with trees. Partial cutting modifies the microclimate, and this effects establishment, survival, and growth of lichen, tree regeneration, and other vegetation species. Important microclimate variables in the partial-cut openings include near-ground air temperature (and associated frost events), soil temperature, and soil moisture.

Beginning in the late 1990s, an outbreak of the mountain pine beetle (*Dendroctonus ponderosae*) started in west-central British Columbia. This outbreak spread rapidly throughout the Interior of British Columbia to encompass an estimated 18.1 million ha by 2012 (Rex et al. 2013). Beetle-caused tree mortality was first documented in the partial cut blocks of the Itcha-Ilgachuz research project in 2003. By 2008, mortality in the mature forest of the research blocks averaged 61% (Waterhouse 2011). This large-scale disturbance throughout the northern caribou habitat has raised new research questions

(Armleder and Waterhouse 2008; Daintith and Waterhouse 2015), such as:

- How will the mostly dead forest surrounding the partial cut openings affect caribou forage species and habitat use, as well as tree regeneration?
- How will tree mortality and subsequent degeneration through foliage, branch, and bole loss change the microclimate within the partial cut openings?

Sagar et al. (2005) described microclimate in the Itcha-Ilgachuz project area from 1997 to 2003 in the irregular group shelterwood (whole tree harvested) and paired clearcut treatments. Over the 7-year period, all blocks had frequent and often severe (air temperature < – 4 °C) frosts throughout the growing season. The partial cut treatment substantially reduced the number and severity of frosts, especially on the edges (north or south) of the small openings. Many studies have demonstrated that residual forest cover in the form of shelterwoods or small openings reduces the incidence of frost and raises nighttime minimum air temperatures (Hungerford and Babbitt 1987; Zasada et al. 1999; Pritchard and Comeau 2004; Voicu and Comeau 2006).

Sky view factor, when used as a way of quantifying the residual forest cover, has been shown to be correlated with increased minimum air temperatures (i.e., lower sky view factors increase minimum air temperature) (Groot and Carlson 1996; Blennow 1998) and lessened duration of frost (Sagar and Waterhouse 2010). Although loss of canopy elements attributed to mountain pine beetle attack will likely increase sky view factor, the remaining tree boles still obscure a significant portion of the sky. It has also been shown that the canopy and boles of large trees enhance aerodynamic mixing of warmer air down to the surface (Granberg et al. 1993). Larger shrubs and advanced regeneration also contribute to lower sky view factor from the viewpoint of small seedlings (~ 15 cm in height). Sagar (2014) presented anecdotal evidence that advanced regeneration in a shelterwood lowered the duration of frost at ground level.

Sagar et al. (2005) showed that partial cuts had lower soil temperature and soil temperature index (STI) values compared with their paired clearcuts. Harvesting of timber increases solar irradiance at the soil surface, which warms the soil (Chen et al. 1993; Bhatti et al. 2000). Even within partial cuts, the north-edge (south-facing) microsites were the most favourable for seedling growth, with the highest soil temperatures, earlier snow-free dates, and more solar irradiance. With the increasing light transmittance related to canopy loss in beetle-attacked areas, we might expect more solar irradiance to reach the ground in the partial cuts, increasing soil temperature and accumulated STI.

Human-caused disturbances in the form of clearcuts and small openings, as well as natural disturbances such as a pine beetle outbreak, modify the hydrologic cycle by eliminating overstorey vegetation, which both intercepts a significant portion of annual snow and rainfall and also uses a large portion of water received by the soil through canopy transpiration (Spittlehouse 2006; Silins et al. 2007; Schnorbus 2011; Winkler et al. 2014). Mature, high-elevation forests intercept 20–30% of annual snow and rain, as shown in a study from the southern interior of British Columbia (Spittlehouse et al. 2004; Winkler et al. 2010). Small openings, similar to clearcuts, have more water reaching the soil surface compared to mature forest; however, unlike clearcuts, the root systems from the surrounding uncut forest can access soil water within small openings. With the death of surrounding mature trees during the middle of our study period, we would expect increased water availability within the small openings.

The progression of hydrological properties after natural or human-caused disturbances to a mature forest state has been called "hydrologic recovery" (Schnorbus 2011). This recovery accompanies the development of vegetation over time, including tree regeneration in both beetle-killed stands and clearcuts. Standing dead trees and vegetation in beetle-killed stands moderate the hydrologic cycle (i.e., reduce water yield) in comparison to clearcuts. Teti (2009) estimated that it will take 20–25 years for clearcuts to catch up with beetle-killed stands in this respect. Brown et al. (2013) showed that evapotranspiration from an attacked forest in north-central British Columbia was maintained at pre-attack levels due to increased growth of understorey vegetation and surviving mature trees. However, the beetle-killed forests in our study area lack a significant amount of understorey vegetation and tree regeneration, and clearcut regeneration grows faster than that in partial cut openings owing to more light and warmer soils. This may lead to a relatively slower hydrological recovery (more available water and higher soil moisture) in the partial cut openings compared to the clearcuts.

In our study, the continuum of changing microclimate conditions during the 16-year period since the openings were created in the partial cut blocks is examined within the context of human-made and natural disturbances. The key environmental variables examined were near-ground air temperature, soil temperature, soil moisture, and snow cover duration. These variables interact with biological variables, such as tree death and vegetation abundance (herb, shrub, terrestrial lichen), which in turn affect caribou habitat quality. The objectives of this study were to:

1. compare the key environmental variables between blocks (elevational effect) and treatments (clearcut and irregular group shelterwood with whole-tree harvesting partial cut), and between microsites within partial cut openings (north and south edges and centre); and
2. examine temporal changes occurring to environmental variables in the context of the changing biological environment.

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 (Figure 1). The five study blocks in the main trial are located within 30 km of Satah Mountain (52°28'N, 124°43'W). For microclimate measurements, three blocks were selected to cover the 1290–1640 m elevational range of the study area: block 1 (1290 m) is in the very dry, cold Sub-Boreal Pine–Spruce (SBPSxc) subzone; block 3 (1420 m) is transitional between the SBPSxc and MSxv subzones; and block 5 (1640 m) is in the very dry, very cold Montane Spruce (MSxv) subzone. The forest canopy throughout the study area is almost exclusively lodgepole pine. Soils in the study area are orthic dystric brunisols with a sandy loam texture on glacial till parent material.

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. The Lodgepole pine–Grouseberry–Feathermoss site

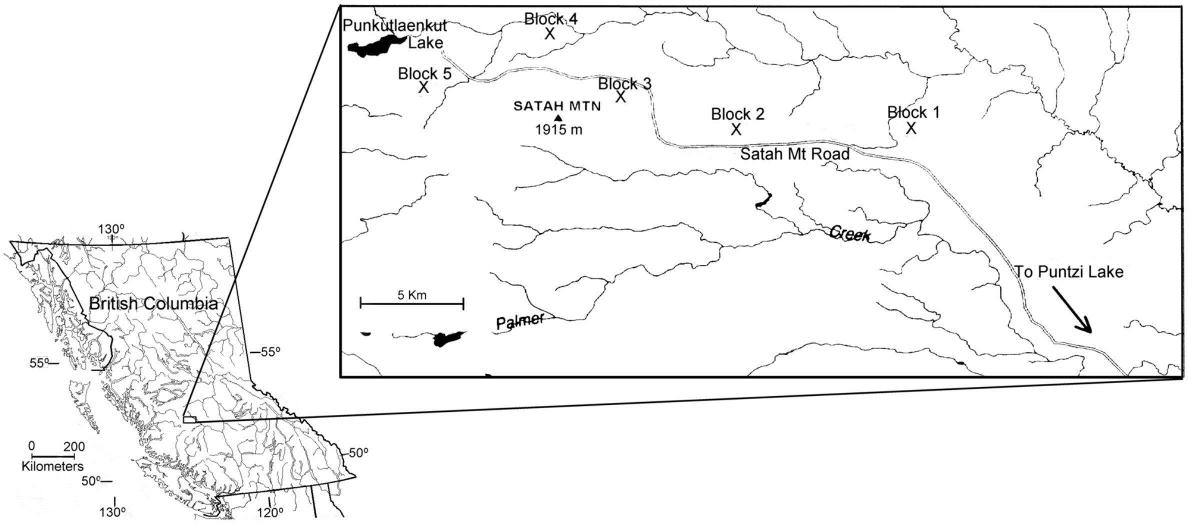


FIGURE 1 *Location of study area within British Columbia and positions of blocks 1–5 near Satah Mountain.*

series (MSxv/01) is predominant in the MSxv blocks. Understorey 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 is present (i.e., *Pleurozium schreberi*, *Ptilium crista-castrensis*, and *Dicranum* spp.) (Steen and Coupé 1997).

The SBPSxc subzone occurs at elevations below the MSxv subzone along the east side of the Coast Mountains and extends as far north as the Rainbow Range. In block 1, the Lodgepole pine–Kinnikinnick–Feathermoss site type (SBPSxc/01) is the predominant site series. Understorey 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).

2.2 Study Design and Treatments

The set-up of the main research trial was based on a randomized block design. The five blocks were selected from several operational blocks scheduled and approved for harvesting. Each 60–80 ha study block was split into four 15–20 ha treatment units and randomly assigned a silvicultural system. The treatments were: (1) no harvest; (2) irregular group shelterwood with stem-only harvesting (IGS–SO); (3) irregular group shelterwood with whole-tree harvesting; (IGS–WT) and (4) group selection with stem-only harvesting (GS–SO) (Figure 2).

Harvesting on the trial blocks was done between January and April, 1996. The IGS systems were designed to remove 50% of the area every 70 years, using small openings. In both of the shelterwood treatments, the area cut averaged 39%, openings were about 30 m in diameter, and skid trails were 3–4 m wide.

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 at

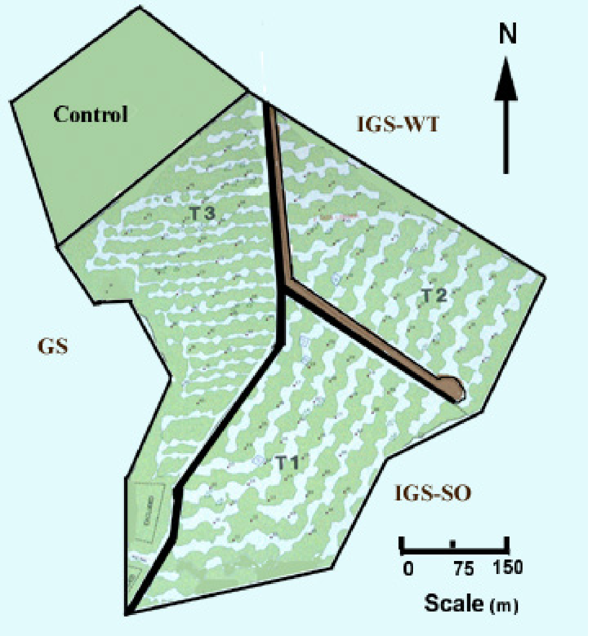


FIGURE 2 *Layout of partial cut treatments in block 5 (GS = group selection with stem-only harvesting; IGS–WT = irregular group shelterwood with whole-tree harvesting; and IGS–SO = irregular group shelterwood with stem-only harvesting).*

similar elevation to the study blocks. Suitable clearcuts were located adjacent to blocks 1 and 3. For block 5, the paired clearcut used for the planted stock study and microclimate monitoring was 1.2 km from block 5, and the clearcut used for the lichen and vegetation studies was adjacent to block 5. Two different clearcuts were used because of the timing of the harvesting and site preparation treatments. The clearcut paired with block 1 was harvested at the same time as the trial block. The clearcut paired with block 3 was harvested 1.5 years before the trial block, during the summer of 1994. The clearcut paired with block 5 for the planted stock and microclimate study was harvested 4–6 months before the trial block, whereas the other clearcut used for the lichen and vegetation study was harvested 6–11 months after the trial block.

2.3 Data Collection at Permanent Sample Plots

2.3.1 Vegetation A grid of 2 m^2 vegetation sampling plots was installed in each no-harvest and partial cut treatment unit (36–50 plots) within the trial blocks and the three clearcut blocks (40 plots each). The percent cover of herbs, dwarf shrubs, shrubs, and regeneration less than 1.3 m tall was visually estimated within the plot. For regeneration over 1.3 m tall the percent cover was estimated in two layers: a lower layer (under 1.5 m) that was visually estimated, and an upper layer (over 1.5 m) that was measured with a moosehorn. The moosehorn instrument is a periscope that vertically projected a grid of points at 12° (Waterhouse et al. 2011), and the grid points touching the tree canopy were converted to percent cover. The vegetation data were collected by layer, but an overlap occurred between the layers, especially between the lower and upper canopy of regeneration taller than

1.3 m. All treatments in the trial blocks were measured in 1995 (pre-harvest), 1998, 2000, 2004, and 2008. The clearcuts were measured in 2001, 2005, 2008, and 2014.

2.3.2 Light and sky view factor To assess sky view factor and light transmittance, canopy photographs were taken in 2007 at each vegetation sampling plot. The photographs were retaken in 2013 in the no-harvest control and IGS–SO treatments in all five blocks. Photo locations were subdivided into forested (> 3 m from opening edge), forest edge (< 3 m from opening edge), open edge (in opening < 2 m from edge), and open (> 2 m from edge). See Teti (2007) and Waterhouse and Dunbar (2008) for a description of the procedures used for fieldwork and data analysis. Analysis yielded estimates of seasonal (9 April–1 September) daily average values for direct and diffuse solar radiation, as well as canopy transmittance and sky view factor. Light transmittance is the ratio of solar radiation (direct and diffuse) reaching the photograph height of 1.3 m to that incident on the top of the canopy. Sky view factor is the fraction of total long-wave radiation incident on a horizontal surface that has been received from the sky (Oke 1987).

2.3.3 Tree mortality attributed to mountain pine beetle In 1995 (pre-harvest), the three closest overstorey canopy trees to each permanent sample plot were selected for an arboreal lichen abundance survey. The sample trees had a minimum diameter at breast height (1.3 m) of 10 cm. In the 2004 assessment, the wildlife tree class (1 = alive; 2 = in decline; 3 = recently dead, > 75% bark; 4 = 25–75% bark; 5 < 25% bark) and mountain pine beetle attack were recorded. The beetle attack on dead trees in classes 4 and 5 most likely resulted from an earlier infestation in the 1980s. Recently dead trees were most likely attacked by mountain pine beetle in 2003. In 2008, the trees were classified as alive (= 1) or dead (= 5), with or without mountain pine beetle, and whether they were standing or fallen. An estimate of mortality was made in 2006 from the permanent growth and yield plots ($n = 20$ plots, 16.93 m radius; one per treatment unit). The percentage of dead trees was based on those of 12.5 cm or larger diameter at breast height recorded as alive in 1996 ($n = 1296$) but dead in 2006. This measurement assumes that most were beetle-killed trees, with the current green attack excluded.

2.4 Weather Station Locations and Instrumentation

This project monitored microclimate in the IGS–WT treatments and clearcuts from 1997 to 2013. One opening was randomly selected in the block 1, 3, and 5 partial cut treatments. All clearcut microclimate measurement locations were on flat to gently sloped ground at least 50 m from the forest edge. The soil type, elevation, slope, and aspect of the clearcuts were very similar to the partial cuts, except in block 5 where the climate station in the paired clearcut was on a slight, north-facing slope (2%) and the one in the partial cut was on an east-facing slope (8%).

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, soil and air temperature were averaged over the two locations. In the partial cut treatments, soil and air temperature were monitored at one location in each of the three microsites within the small openings. 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.

The instrumentation at each station included unshielded thermistors mounted 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 (Model 107; Campbell Scientific, Edmonton, Alberta) were 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 (Model 207; Campbell Scientific). Soil volumetric water content was measured with water content reflectometers (Model CS615; Campbell Scientific) at 3 cm beneath the mineral/organic interface. The water content reflectometers were calibrated against gravimetric samples for the soil type at each location. Rainfall was measured in the clearcuts only, using tipping bucket rain gauges (Models TE525 or TE525m; Texas Electronics Inc., Dallas, Texas). The measurements made in blocks 1, 3, and 5 are summarized in Table 1.

TABLE 1 *Summary of microclimate measurements made in blocks 1, 3, and 5*

Treatment	Measurement	Microsite	Replicates
Clearcuts	Air temperature, 15 cm	Open	2
	Air temperature, 1 m (block 5 only)	Open	1
	Soil temperature, 1 cm	Open	2
	Soil temperature, 15 cm	Open	2
	Soil water potential, 3 cm	Open	1
	Soil water potential, 15 cm	Open	1
	Volumetric soil water content, 3 cm	Open	1
	Rainfall	Open	1
Partial cuts	Air temperature, 15 cm	North edge	1
	Air temperature, 15 cm	Centre	1
	Air temperature, 15 cm	South edge	1
	Soil temperature, 1 cm	North edge	1
	Soil temperature, 1 cm	Centre	1
	Soil temperature, 1 cm	South edge	1
	Soil water potential, 3 cm	North edge	1
	Soil water potential, 15 cm	North edge	1
	Volumetric soil water content, 3 cm	North edge	1

The air temperature thermistors had a small nighttime radiation error (about − 0.5°C) compared to the fine-wire thermocouples (Sagar et al. 2005). Some of the below-ground soil temperature sensors failed over time when water infiltrated through cracks in the epoxy or shrink tubing surrounding the thermistors. Over time, gypsum blocks are expected to degrade as soil chemistry and freeze–thaw cycles cause the gypsum to dissolve. Their expected useful lifetime is 2–5 years. Data from the 2004 and 2005 growing seasons indicated failing gypsum blocks.

Upgrades to, and replacement of, instruments were carried out at all blocks during May 2006. Soil thermistors were replaced with twisted and soldered thermocouples (24 AWG Chromel-Constantan) placed in a 3 cm long piece of quarter-inch brass tubing and encased in epoxy resin. Air temperature thermistors were replaced with unshielded, 30 AWG Chromel-Constantan (Omega Engineering Inc., Laval, Quebec) fine-wire thermocouples, constructed by twisting and soldering the wire, which gave an effective diameter of 0.5 mm for the junction. A panel temperature reference thermistor (Model 44002A; YSI Inc., Yellow Springs, Ohio) was also added to all dataloggers at this time to support the thermocouple measurements. Because all datalogger measurement channels were used up, measurement of 1 cm soil temperature for north-edge locations in the partial cuts was discontinued at this time. All gypsum blocks were replaced with new sensors (Model 207; Campbell Scientific). Finally, the tipping bucket rain gauge in the block 3 clearcut was replaced with a Texas Electronics (Model TE525WS) rain gauge.

Monitoring of microclimate began at blocks 1 and 3 in 1997, and in 1998 at block 5. Soil moisture monitoring was added in June 1999, and rain gauges were added to the clearcuts in June 2000. An unshielded fine-wire thermocouple was installed at a height of 1 m on the block 5 clearcut to monitor air temperature above the winter snowpack, starting in 2005. Data were collected and stored using Campbell Scientific, Model CR10X dataloggers. All climate stations were dismantled in the fall of 2013. For more details, refer to Sagar et al. (2005).

2.5 Analysis

Analysis focussed on growing season microclimate conditions in the blocks. To standardize comparisons among different years and blocks, the growing season was defined as the period from 1 May through 30 September. This period was used to calculate soil temperature index (STI), mean soil temperature, and mean minimum air temperature. The frequency and severity of summer frost events was determined for the period 1 June until 15 August, when the current year's growth on seedlings is most sensitive to frost damage. Bud flush for lodgepole pine typically occurs after 1 June in the MSxv and higher elevations of the SBPSxc.

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 is 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 phrase "soil temperature index" is 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 as 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 −2.0 MPa, with the often-quoted value 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 block.

The snow-free date was determined for each year and block 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 was assumed to be completed 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.

3 RESULTS AND DISCUSSION

3.1 Tree Mortality Attributed to Mountain Pine Beetle

Attack of mature lodgepole pine by the mountain pine beetle is a recurring natural disturbance event on British Columbia's Chilcotin Plateau. According to Waterhouse et al. (2011), the mountain pine beetle outbreak in this area during the mid-1980s resulted in 7–21% mortality of mature lodgepole pine on the study blocks. As of 2003, 3% of the permanently marked sample trees in the study blocks were dead from new mountain pine beetle attack. Tree mortality rose to 15% in 2004, 47% in 2006, and 61% in 2008. This remained unchanged as of 2013. Table 2 summarizes the percentage of trees attacked by mountain pine beetle in the IGS–WT treatment units for 2004 and 2008. Mortality in 2004 ranged from 0% in block 5 to 18.9% in block 3. Although the outbreak was slower to reach block 5, by 2008 it had the highest attack rate among the three blocks at 67%.

TABLE 2 *Percent of sample trees attacked by mountain pine beetle in the irregular group shelterwood treatments with whole-tree harvesting in 2004 and 2008*

Block	2004 % dead	2008 % dead
1	9.8	59.1
3	18.9	46.4
5	0.0	67.2

Most of the mountain pine beetle attack on the study blocks occurred from 2004 to 2007 (green attack phase), with needles turning red from 2005 to 2009 (red attack). In the third year after green attack, the needles are dull orange to grey, then drop from the trees (Cole and Amman 1969). On our study site, the bulk of the attacked trees would have been bare by 2010 (grey attack). A small amount of tree fall occurred during the study. From post-harvest (1996) to 2008, 5.0% of the trees within the permanent sample plots of the SBPS blocks fell, and this increased to 5.1% by 2013. By 2008, 4.3% of the sample trees in the MS blocks fell, and this increased to 10.5% in 2013.

3.2 Vegetation Cover

Figures 3 and 4 show time series of average percent cover for each vegetation layer in the IGS–WT treatments (forest and opening locations combined) and clearcuts. For these treatment units, the trend was a decrease in vegetation cover in each layer immediately after logging (1998), followed by increasing vegetation cover with time. The layer containing regeneration taller than 1.3 m was not measured in 1995, so this layer is not included, whereas it is included for 1998. Vegetation cover is higher in block 5, mainly due to greater cover by dwarf shrubs and herbaceous plants. This is a result of more growing season precipitation in the higher-elevation MSxv subzone.

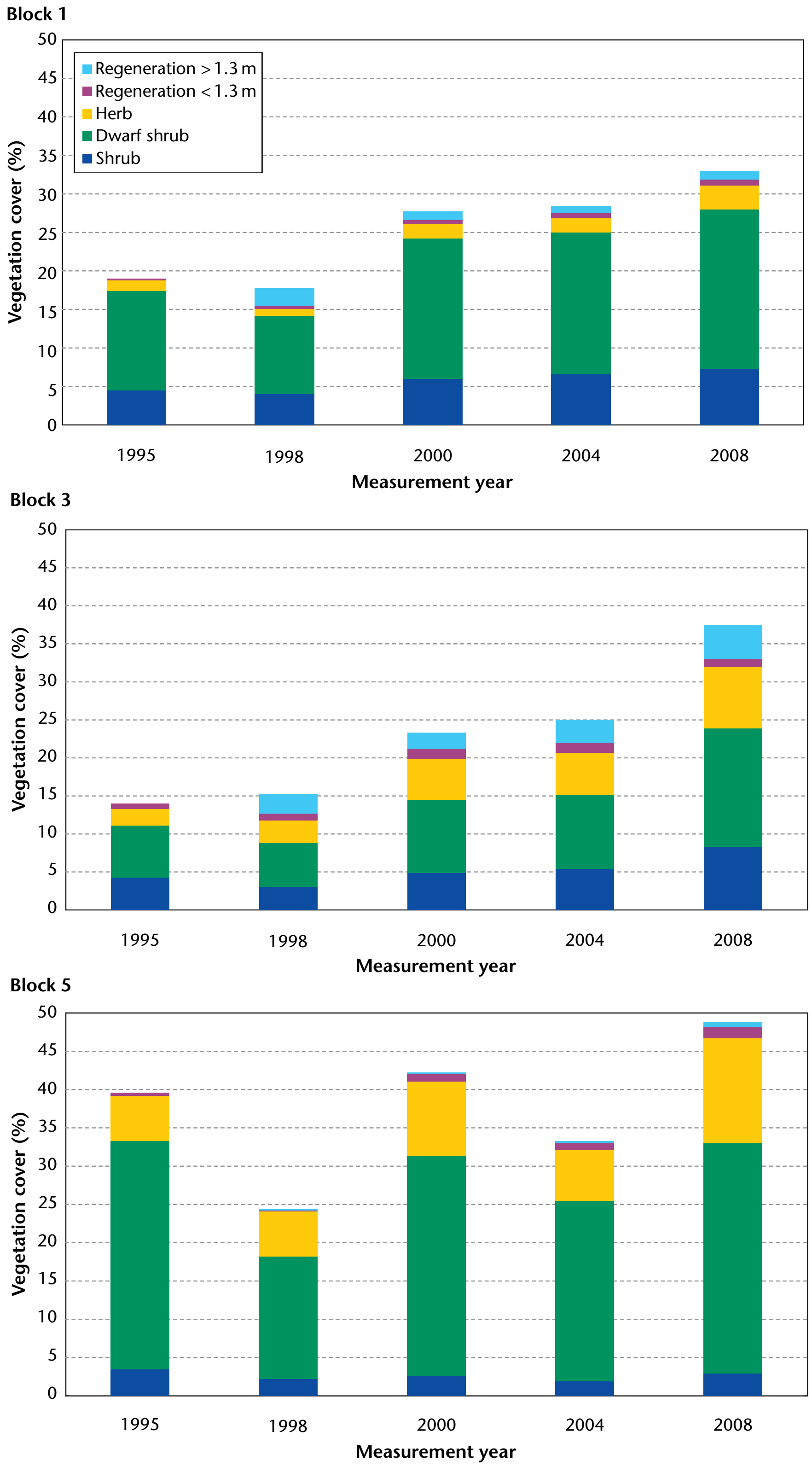


FIGURE 3 *Percent cover by vegetation layer for blocks 1, 3, and 5 in the irregular group shelterwood treatment with whole-tree harvesting (forest and opening plots combined) from pre-harvest in 1995 to 2008.*

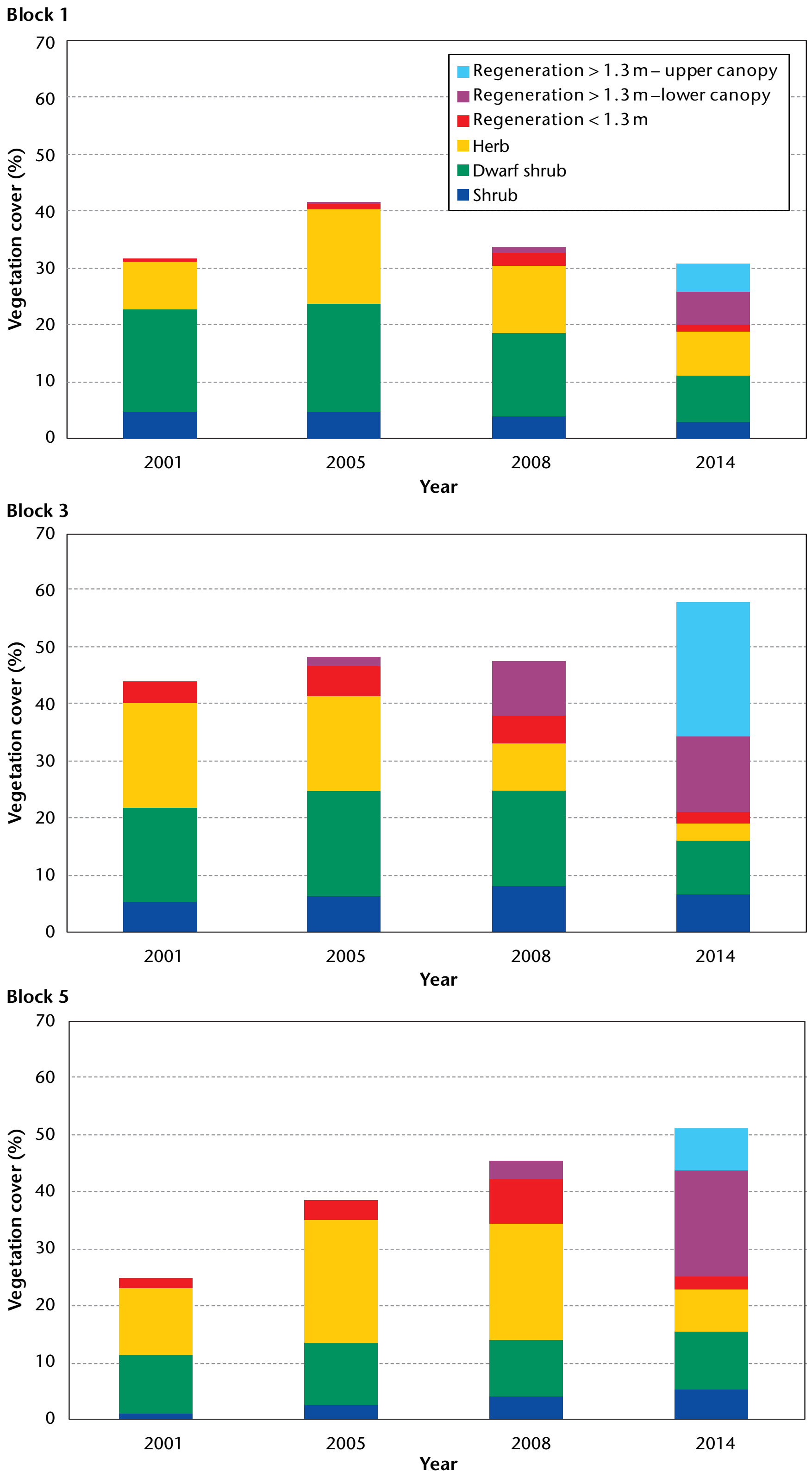


FIGURE 4 *Percent cover by vegetation layer for blocks 1, 3, and 5 in the clearcut treatments from 2001 to 2014.*

In the clearcut treatments, the herb layer increased from 2001 to 2005, then in 2014 it decreased in blocks 1 and 5, whereas in block 3 it consistently decreased from 2001 to 2014. The dwarf shrub layer in blocks 1 and 3 also increased from 2001 to 2005, then declined; however, in block 5 it remained unchanged from 2001 to 2014. The shrub layer increased modestly over time in block 5 but remained stable in blocks 1 and 3. One clear trend is that the percent cover of small (< 1.3 m) and large (> 1.3 m) regeneration increased up to 2008. By 2014, large regeneration had increased dramatically in all blocks (Figure 4) as a result of recruitment from the smaller regeneration class. Although the percent cover of regeneration is relatively small in 2008, a good portion of the large regeneration was 1.3–2 m tall, representing a significant amount of leaf area index and beginning to visually dominate the clearcuts. By 2014, the regeneration was the dominant vegetation layer, with many tree heights exceeding 2 m.

Figure 5 shows light transmittance and sky view factor for the no-harvest and IGS (partitioned by forested and open locations) treatments determined from canopy photographs taken in 2007 and 2013. The 2007 sky view factor and transmittance numbers portray the canopy with an undetermined loss attributed to the mountain pine beetle infestation, which began affecting the sites in 2003. Winkler et al. (2014) found little change in canopy transmittance until the fourth year following pine beetle attack in a young (35-year-old) lodgepole pine stand in the southern interior of British Columbia, when transmittance increased approximately 8% from pre-attack levels. The process of canopy loss, with more infested trees dying, the loss of needles from already-dead trees, and possibly some windthrow of dead trees, continued from 2007 to 2013. By 2013, the vast majority of attacked trees were classified as grey attack (no needles). This is reflected in the large increase of transmittance and sky view factor, especially in the no-harvest treatment units (23 and 25%, respectively) and the forested locations within the IGS treatment units (10 and 13%, respectively; see Figure 5). There was only a 3% increase in transmittance and a negligible increase in sky view factor for the IGS-opening locations during the period, and these values are within the measurement error associated with calculating values from canopy photos. The opening loca-

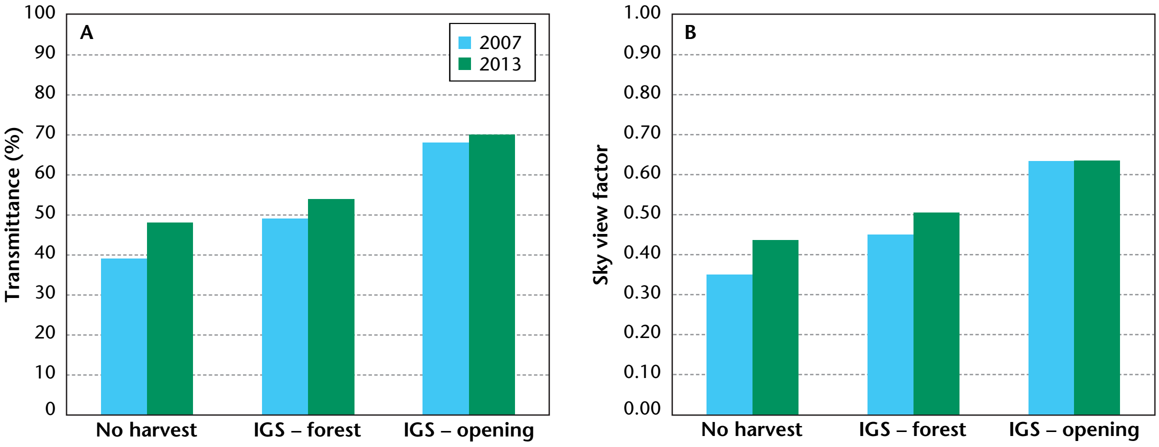


FIGURE 5 *Transmittance (A) and sky view factor (B) based on canopy photos taken in 2007 and 2013 in the no-harvest and irregular group shelterwood (IGS) with stem-only harvesting treatments (separated into forest and opening locations).*

tions are less influenced by loss of canopy and boles in the surrounding forest because there is already a higher proportion of open sky. Also, by 2013 it is possible that advanced regeneration (> 1.3 m) in the openings offset increases in transmittance and sky view factor caused by loss of canopy and boles in the surrounding forest.

3.3 Soil Temperature

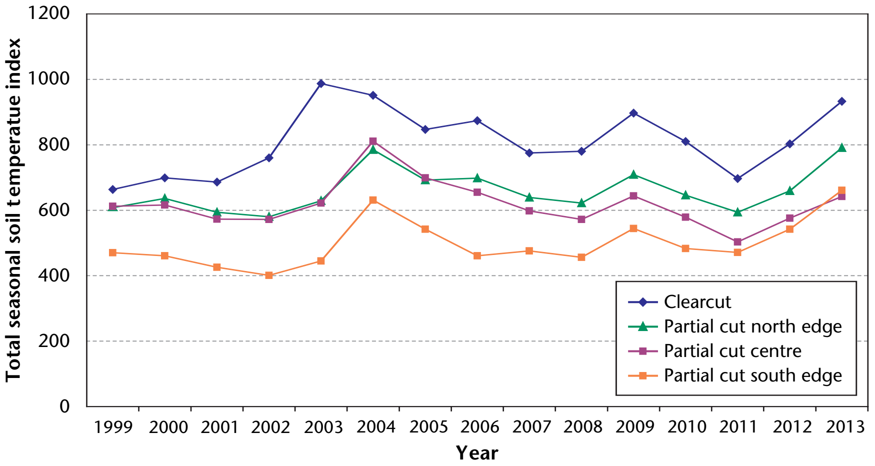
Low soil temperature affects the growth and vigour of seedlings by hampering root uptake of water and nutrients, thereby decreasing a seedling's ability to photosynthesize (Delucia 1986). Lajzerowicz et al. (2004) showed that growth and photosynthesis in Engelmann spruce and subalpine fir seedlings decreases as soil temperature decreases within the range of 5–15°C. Sagar et al. (2005) reported that 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. Appendix 1 gives the seasonal (1 May–30 September) mean 15 cm soil temperature for all blocks, treatments, and microsites over the period 1997–2013. The means over the whole study period range from 6.4°C at the block 5 south-edge microsite to 10.1°C at the block 1 clearcut treatment. Growing season soil temperatures on all study blocks exceeded the 5°C threshold, which is needed for significant root elongation (Lopushinsky and Max 1990).

Figure 6 shows total 5°C STI for each treatment and microsite in blocks 1, 3, and 5 (see Appendix 2 for full data set). The patterns observed at all three blocks are similar, with clearcuts accumulating significantly more STI than partial cut locations and, at least initially, south-edge (north-facing) microsites accumulating the fewest STI among the partial cut microsites. See Sagar et al. (2005) for a detailed discussion of the effects of microsites and block elevation on soil temperature (1997–2003). These patterns are explained by larger solar input to the soil surface in the clearcuts and north-edge locations, given similar surface compositions.

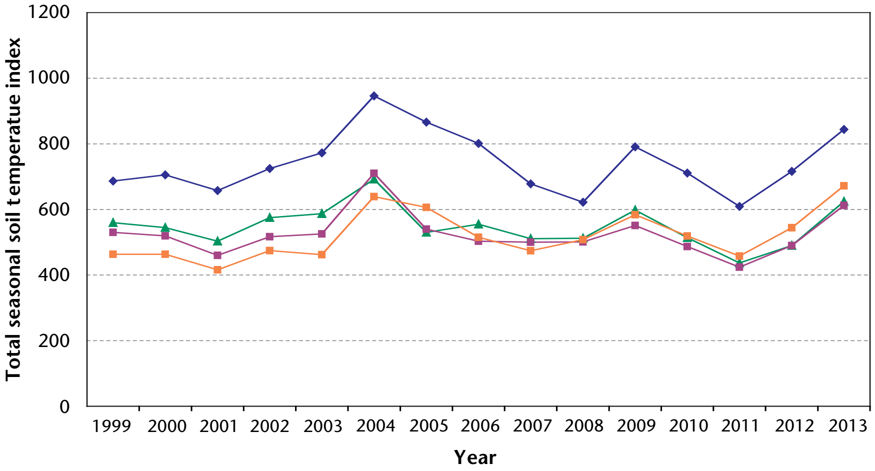
Vegetation cover, including mature trees, would be expected to affect how much solar radiation reaches the ground and thus is an important factor in determining STI accumulation at a given location. Vegetation cover affects soil warming in several ways, one of which is through its effect on snow cover and snow cover ablation rates. Teti (2009) found that 64% of the variance in snow cover ablation rates could be explained by light transmittance. The second way is through regulation of the amount of net radiation available at the soil surface to heat the soil once snowmelt is complete.

Little warming of soil can take place when snow cover is present; therefore, the date when snowmelt is complete in the spring (see Section 3.6) marks the beginning of significant soil warming and STI accumulation. Based on this observation, the snow-free date should be a strong determinant of total seasonal STI accumulation. To test this hypothesis, we performed a linear regression analysis to see how much of the total seasonal STI variance could be attributed to snow-free dates in the clearcuts and centre microsites of the partial cut treatments (Table 3). Snow-free date explained up to 54% of the variance (block 3 clearcut) and was above 25% for all but the block 5 partial cut. The slopes of the linear regression lines were significant ($\alpha = 0.05$) for all locations except the block 5 partial cut. The 2004 growing season, with its peak or near-peak STI accumulation, had the earliest snow-free dates for blocks 1 and 3. The foregoing discussion suggests that snow-free date may explain a significant amount of the year-to-year variation in seasonal total STI

Block 1



Block 3



Block 5

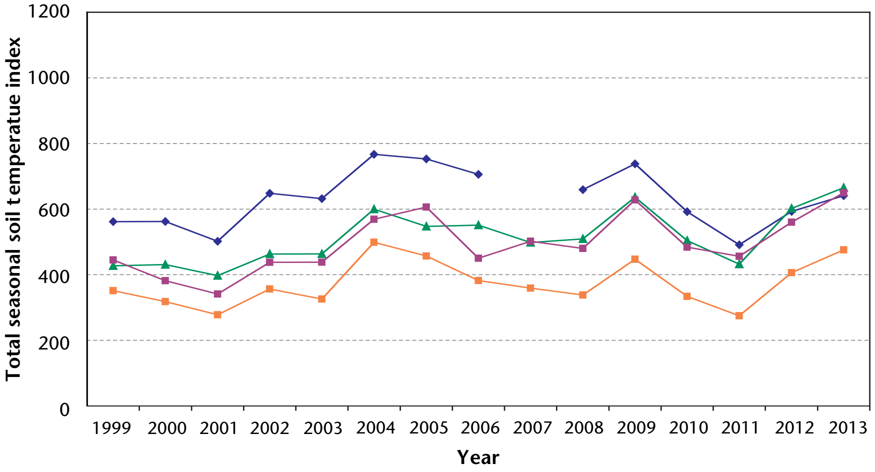


FIGURE 6 *Growing season (1 May–30 September) total 5°C soil temperature index based on 15 cm soil temperatures for all microsites and treatments in each block (1997–2013).*

TABLE 3 *The adjusted percent of variance (R^2), probability, and linear regression model for day of year versus total seasonal soil temperature index accumulation in the clearcuts and the centre microsite of the partial cut treatments for the period 1999–2013*

	Block 1			Block 3			Block 5		
Treatment	R^2	P	Equation	R^2	P	Equation	R^2	P	Equation
Clearcut	0.27	0.029	$Y = -5.33X + 1400$	0.54	0.001	$Y = -7.09X + 1585$	0.39	0.010	$Y = -6.40X + 1496$
Partial cut	0.49	0.003	$Y = -5.61X + 1300$	0.44	0.004	$Y = -5.45X + 1202$	0.09	0.159	$Y = -3.61X + 969$

accumulation, along with other factors such as total seasonal solar irradiance and air temperature.

Figure 6 may also be interpreted in light of the changing vegetation cover over time at the blocks. For this purpose, it is useful to focus on the changing relationships among the various treatments. Even though regeneration cover and height has increased significantly in the clearcuts and forest openings (1997–2013), it does not impede warming as much as the overstorey canopy. The overstorey has transitioned from predominantly live to mostly dead without needles over the study period, yet it still intercepts solar radiation and reduces sky view factor. Light transmittance, and therefore solar input, has not significantly increased in the openings from 2007 to 2013, so mortality (mostly needle loss) in the adjacent forest is not substantially influencing STI. There was still generally more STI accumulated in the clearcuts than the paired partial cuts in the later part of the study period.

In the future, the total STI accumulation among the treatments and microsites will converge because of forest regrowth in both the clearcuts and partial cuts. Figure 6 shows evidence that this process is starting. In block 1, STI accumulation at the centre microsite shows a relative decrease over the period 2005–2013 and converges with that at the south edge. This could be caused by specific elements of advanced regeneration that are beginning to shade the centre location (best growing location). In the block 3 partial cut, the spread among microsites has lessened over time. This could be related to the increasing size of regeneration and extensive fall of mature trees adjacent to this particular opening. In block 5, the difference between the clearcut and the warmest partial cut microsites (north and centre) was fairly large in the beginning of the study but was effectively zero by 2013. Regeneration growth may cause a decreasing amount of solar radiation to reach the soil surface in the clearcut, along with a relative increase in solar radiation at the north and centre microsites (foliage loss on dead trees or tree fall) but not the south edge. These changing patterns suggest that the effects of natural disturbance and also regrowth of vegetation cover are not homogeneous over the landscape.

3.4 Air Temperature

Air temperature is an important environmental factor that affects 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 by Delucia and Smith (1987), and Lundmark and Hällgren (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.

Harvesting, particularly clearcutting, can also cause an increase in damaging summer frost events related to the loss of the forest sheltering effect. When circular openings had a diameter larger than about 0.6 tree heights, increasing sky view factor (> 0.3) caused lower long-wave radiation at the surface and lower nighttime minimum air temperatures than in the forest, especially in the opening centre (Groot and Carlson 1996). Jordan and Smith (1995) also demonstrated that a reduction in sky view factor raised leaf temperatures in a subalpine meadow.

Sagar et al. (2005) discussed the frequency and severity of summer growing season frost events at the high-elevation blocks in this study. Summer frost was still frequent in all blocks, treatments, and microsites over the period 2004–2013, and the patterns observed are similar to those from 1997 to 2003 (Appendix 3). During the 76-day period from 1 June to 15 August there were, on average, more than 40 nights when 15 cm air temperature dropped below 0°C in the block 1 and 5 clearcuts. Severe frost (air temperature < – 4°C) occurred in all blocks, treatments, and microsites. Extreme minimum air temperatures (lower than – 9°C) have also been recorded in the clearcuts during the growing season (Appendix 4). Frequency and severity of growing season frosts were lower in the partial cut openings than in the clearcuts throughout the study, with approximately twice as many severe frosts in the clearcuts as the partial cut centre microsites. This pattern was also noted for extreme minimum temperatures.

Figure 7 shows annual growing season (1 June–15 August) numbers of frosts (air temperature < 0°C) and severe frosts (air temperature < – 4°C) for all treatments and microsites at blocks 1, 3, and 5 from 1997 to 2013. Throughout the study, clearcut locations had significantly higher numbers of frosts than partial cut microsites, with the exception of block 3 for the period 2008–2013. Among the partial cut microsites, south-edge and centre locations had the most frosts, whereas north-edge locations had the fewest (Sagar et al. 2005). Figure 8 shows growing season mean minimum 15 cm air temperatures (Appendix 5). When Figures 7 and 8 are compared, lower seasonal mean minimum air temperatures are associated with higher frost frequencies. Another notable feature of these figures is the relatively lower numbers of frosts and higher minimum air temperatures during the 2004 and 2005 growing seasons, which was likely related to more cloud cover during these seasons. Cloud cover moderates nighttime air temperatures by decreasing loss of long-wave radiation to the sky. These seasons also had the highest rainfall amounts during the study. This illustrates how the effects of large-scale weather patterns are superimposed on local environmental conditions to influence near-ground microclimate.

During the last 6 years of this study (2008–2013), a trend towards a general decline in the number of growing season frosts occurred at all blocks. Although the absolute numbers of frosts (< 0°C) in the partial cuts are not necessarily at their lowest frequency of the study period, the length of this trend is significant. By 2013, severe frost events (< – 4°C) in all three clearcuts had reached their lowest frequency of occurrence. Figure 8 shows that growing season mean minimum air temperatures rose in most treatments during this period. These trends can be explained by the increasing height and density (Figures 3 and 4) of regeneration in the clearcuts and openings. As the regeneration gets taller, the ground surface surrounding the sensor positions "sees" less sky (lower sky view factor), which leads to increased net radiation and higher nighttime air temperatures.

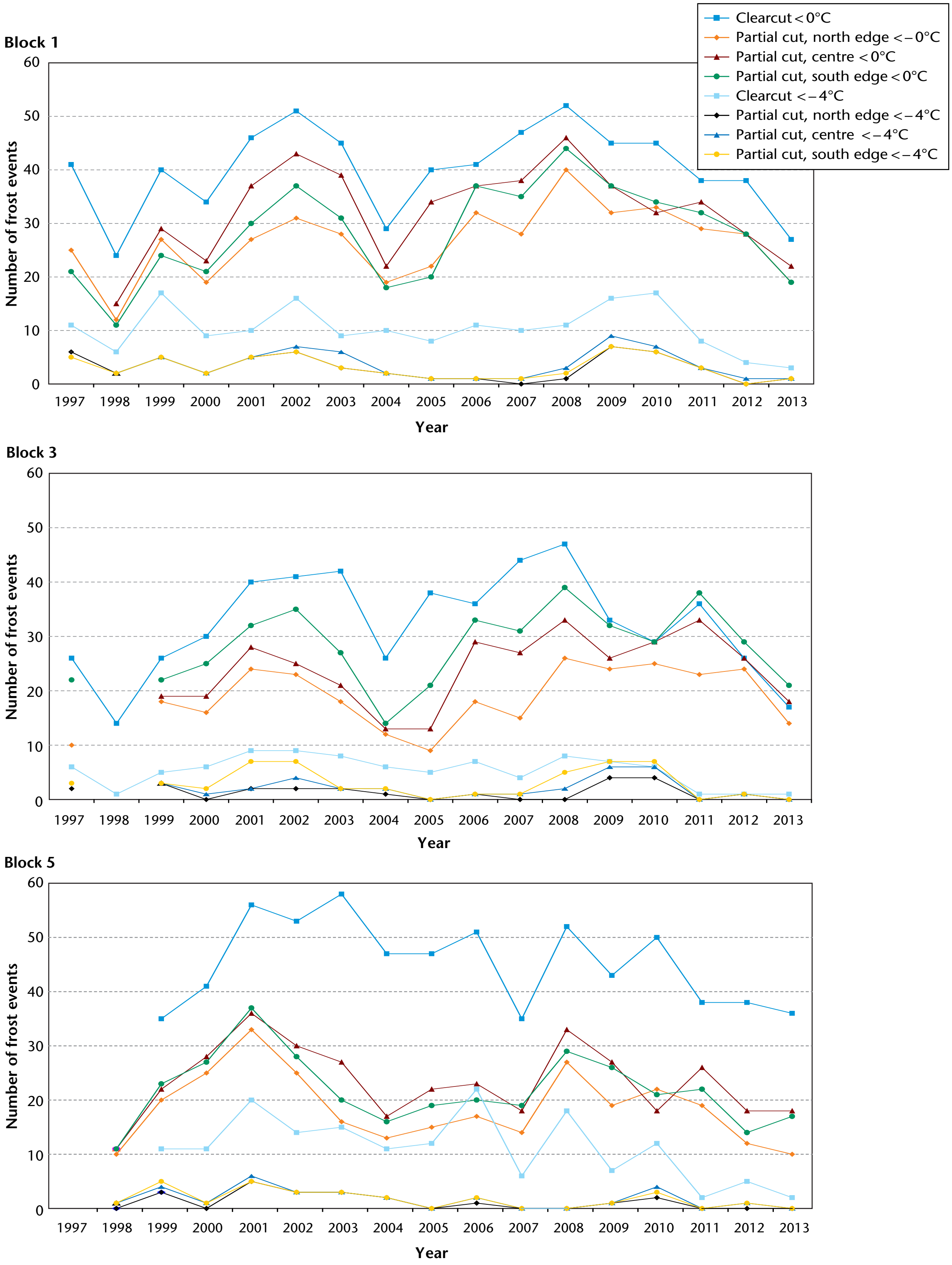
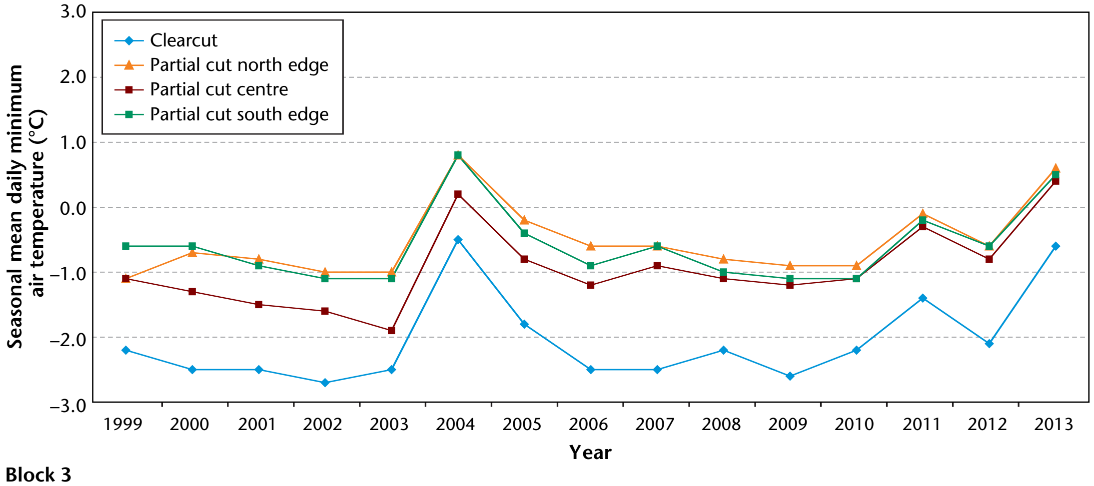
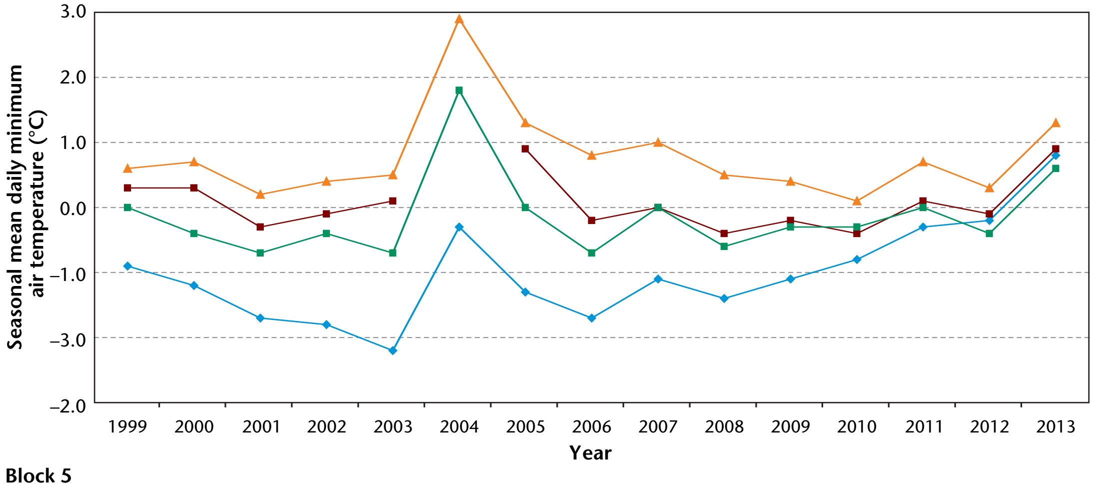


FIGURE 7 *Seasonal (1 June–15 August) total number of frosts (air temperature < 0°C) and severe frosts (air temperature < –4°C) for all microsites and treatments in each block (1997–2013).*

Block 1



Block 3



Block 5

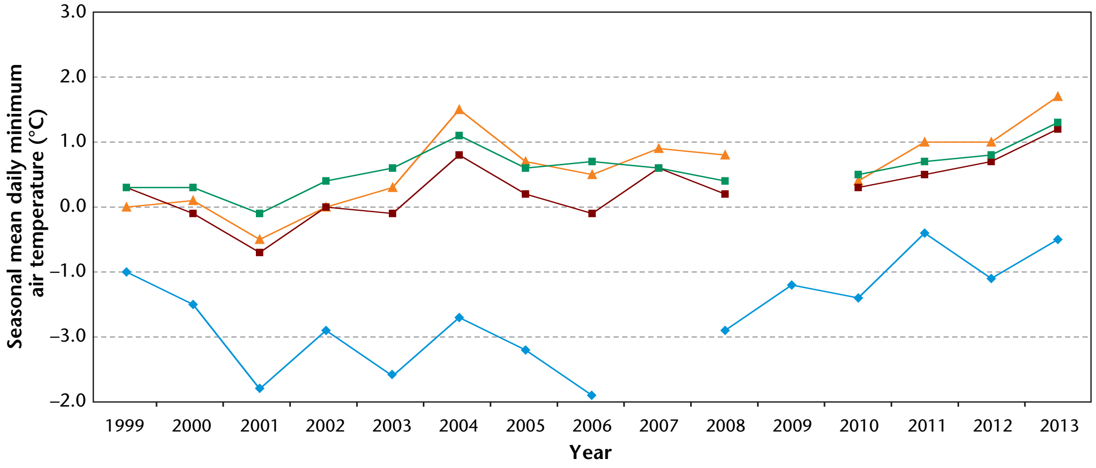


FIGURE 8 *Seasonal (1 May–30 September) mean of daily minimum 15 cm air temperatures for all microsites and treatments in each block (1997–2013).*

At blocks 1 and 3, differences in the number of frosts among the microsites has diminished as the regeneration has grown (Figure 7). This was also noted for STI accumulation at the partial cuts. By 2013, the partial cut microsites at block 1 have nearly identical seasonal mean minimum air temperatures (Figure 8), and the separation between them and the clearcut has decreased. By 2009, the number of frosts in the clearcut at block 3 was no longer markedly higher than that in the coldest partial cut microsite. In fact, during the 2013 growing season, two of the three partial cut microsites had more frosts than the clearcut. All block 3 microsites, including the clearcut, show a convergence in seasonal mean minimum temperatures, beginning in 2008. Because the block 3 clearcut treatment was logged one to two growing seasons earlier than the other blocks, it provides an insight into how the patterns of frost and temperature may change on blocks 1 and 5. As of 2013, the block 3 clearcut has the tallest and densest regeneration of the three clearcuts, which explains the more advanced homogenization of microsites with respect to near-ground air temperatures.

The beetle-caused death of the mature trees followed by needle loss increased sky view factor, especially near the sensors positioned on the edge of openings. Canopy photographs taken in 2007 and 2013 in the IGS treatment units at opening edge locations showed an average increase in sky view factor of 3%. It is difficult to detect in the data whether the loss of sheltering effect caused by the beetle attack had any influence on air temperatures in the near-ground environment. Although sky view factor did increase by a small amount, standing dead trees with no needles still obscure a significant portion of sky and therefore contribute to the sheltering effect. If an effect did occur, then it was likely overwhelmed by the increasing cover provided by regeneration during the last 5 years of the study.

Figure 9 shows cold season (1 October–30 April) daily minimum 1 m air temperature in the block 5 clearcut for each season from 2005 to 2013. There were very few days during these seven seasons when daily minimum air temperature did not drop below freezing, and these days were confined to October and April. Extreme minimum temperatures fell to −40°C or below on a total of 7 days during four winters. The coldest temperature, −46.1°C, was recorded on both 17 and 18 January 2012. Minimum temperatures below −20°C occurred from late October to late April.

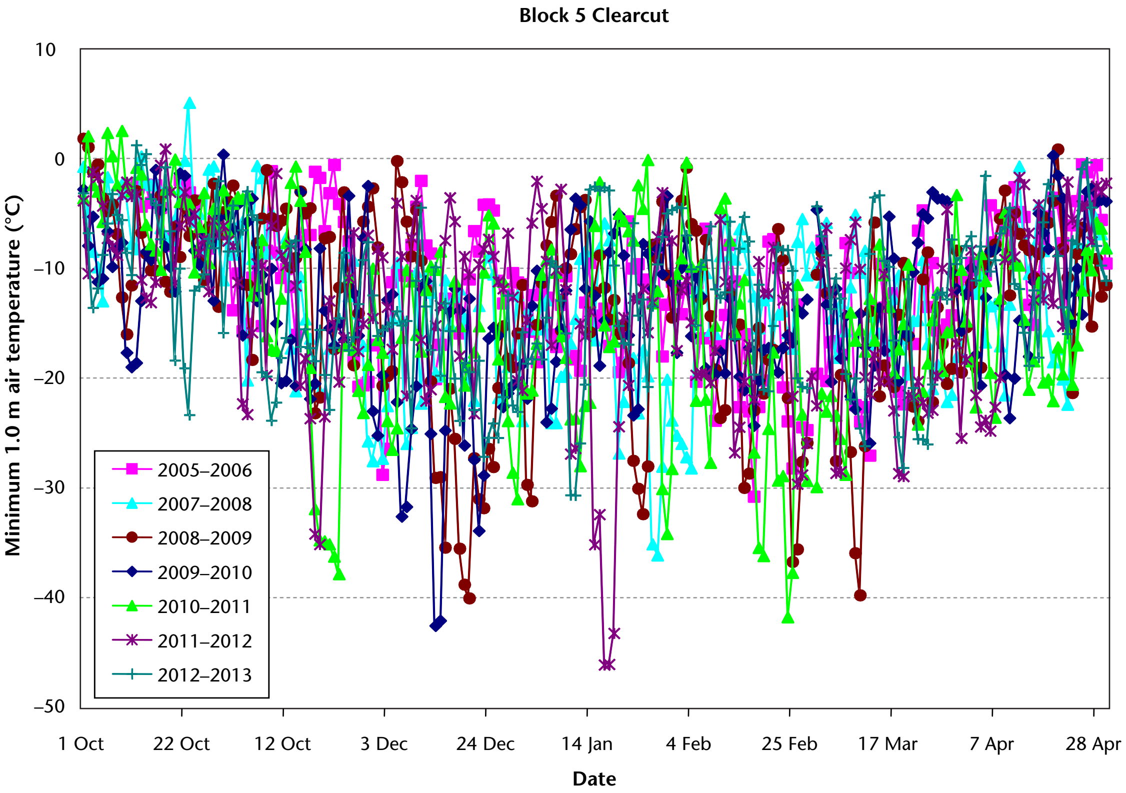


FIGURE 9 *Daily cold season (1 October–30 April) minimum 1 m air temperature in the block 5 clearcut for each year during the period 2005–2013.*

3.5 Precipitation and Soil Moisture

Figure 10 shows total growing season rainfall for the block 1, 3, and 5 clearcuts over the period 2002–2013. Periods of measurement varied from season to season but typically were late May to early October. Appendix 6 contains the complete rainfall data set, including periods of measurement for each year and data notes. Rainfall was greatest at block 5, the highest-elevation block, and typically, but not always, lowest for block 1, the lowest-elevation block. In dry seasons, rainfall ranged from about 75 to 130 mm, whereas in the wettest seasons rainfall ranged from 200 to 300 mm. During the time of this study, the 2004 and 2005 seasons had notably high rainfall. The 2002, 2006, and 2009 seasons had relatively low rainfall at all blocks.

Although volumetric soil water content (θ_v) was measured only at one location in each weather station block, examining trends in θ_v over time can still give insight into the effects of partial cutting and mortality related to the mountain pine beetle in this ecosystem. Comparing soil moisture regimes in the clearcut treatments with those in the partial cut opening provides a useful contrast. Figure 11 compares daily θ_v and rainfall in the clearcut and partial cut treatments of each block during two representative years of this study. The year 2001 illustrates the post-logging period before the mountain pine beetle outbreak in the partial cuts, whereas the year 2008 represents conditions after the beetle outbreak at the point of maximum tree mortality. In 2001, the clearcuts began each growing season with higher θ_v than

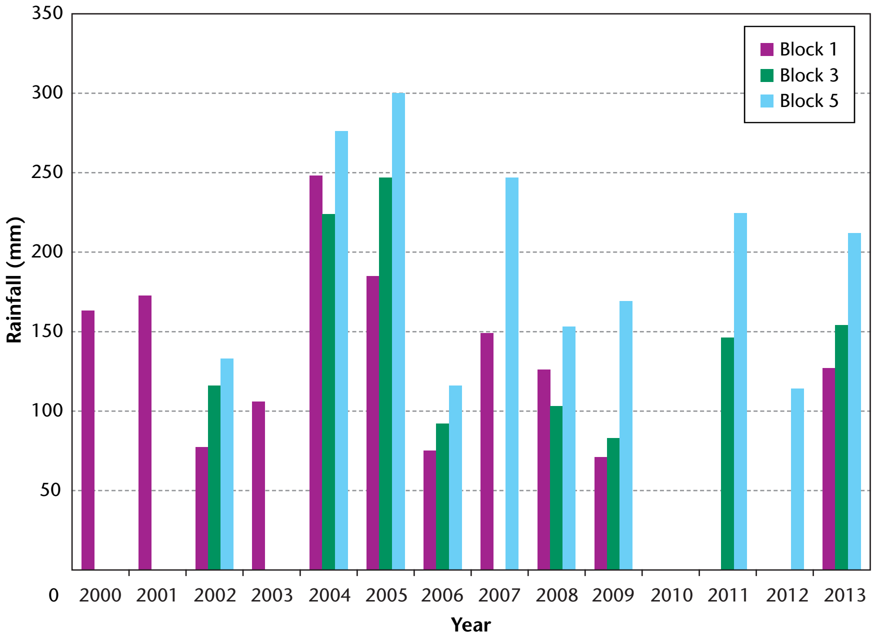
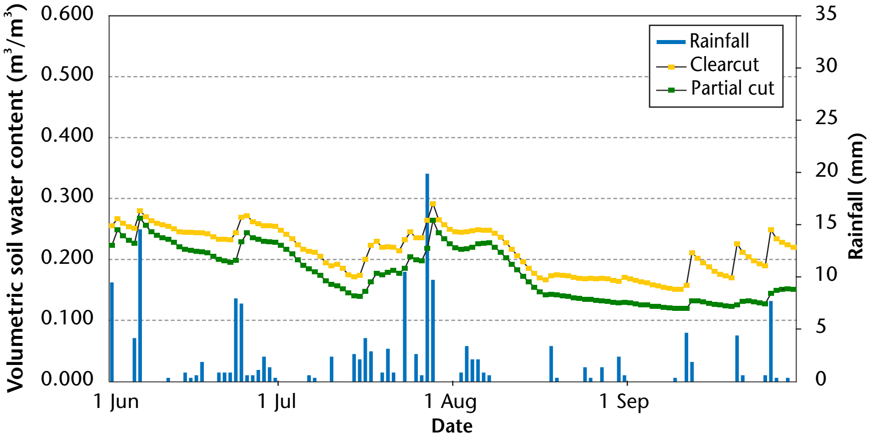


FIGURE 10 *Seasonal total rainfall at the block 1, 3, and 5 clearcuts. Incomplete data have been excluded.*

the partial cuts and this level was maintained throughout the season. Two factors may contribute to this pattern. First, mature forests have lower net of precipitation (rain and snow) reaching the ground than clearcuts (Winkler et al. 2010; He et al. 2013). Second, growing season water use in mature forests is typically higher than that in new clearcuts with relatively little vegetation (Spittlehouse 2006). By 2008, θ_v in the clearcuts was either close to that in partial cut openings, or lower for parts of the growing season. This indicates some fundamental changes in the site water balance. These changes may in part be related to the natural disturbance caused by the mountain pine beetle (i.e., decreased canopy interception and evapotranspiration) and also to the growth of vegetation in the clearcuts and partial cuts. Bhatti et al. (2000) found that the post-harvest vegetative recovery attributed to shrubs, herbaceous plants, and planted jack pine seedlings led to increased soil moisture draw-down in a northern Ontario clearcut.

To further explore the continuum of the changing water balance on these blocks, the mean (1 July–30 September) daily difference in θ_v between the clearcut and partial cut treatments was compared for each block from 1999 to 2013 (Figure 12). In general, the greatest positive difference (i.e., θ_v in the clearcuts was greater than that in the partial cuts) was at the beginning of this period. The difference showed a general decline throughout the period, becoming negative (i.e., θ_v in the clearcuts less than that in the partial cuts) at two of the three blocks, and close to zero in the third block (block 3) by 2013. This shift in water use patterns began before the first significant mountain pine beetle mortality on the blocks in 2004. This indicates that water use on the clearcuts was increasing faster than that in the partial cut openings, likely due to the faster growth of regeneration and herbaceous plants on the clearcuts. In a study of planted stock on the research blocks, Waterhouse et

Block 1 2001



Block 1 2008

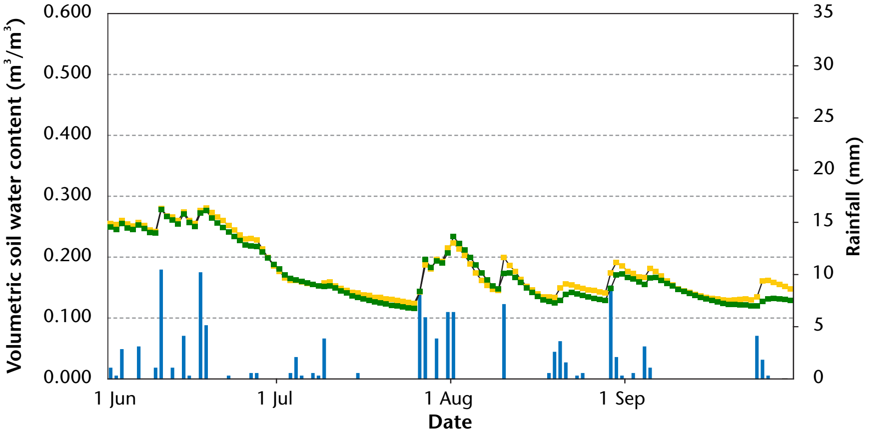


FIGURE 11 *Representative plots showing daily average 3 cm volumetric soil water content and total rainfall (when available) for the 2001 and 2008 growing seasons at each block. Volumetric soil water content is shown for the clearcut and partial cut treatments at each block.*

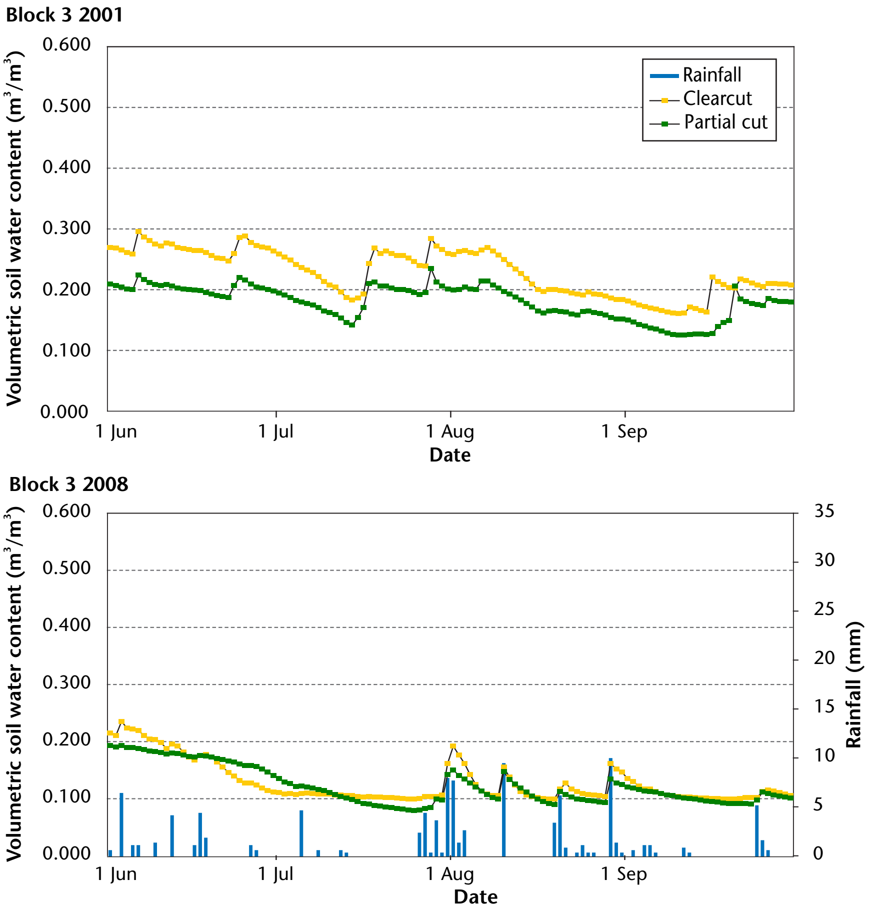


FIGURE 11 *Continued*

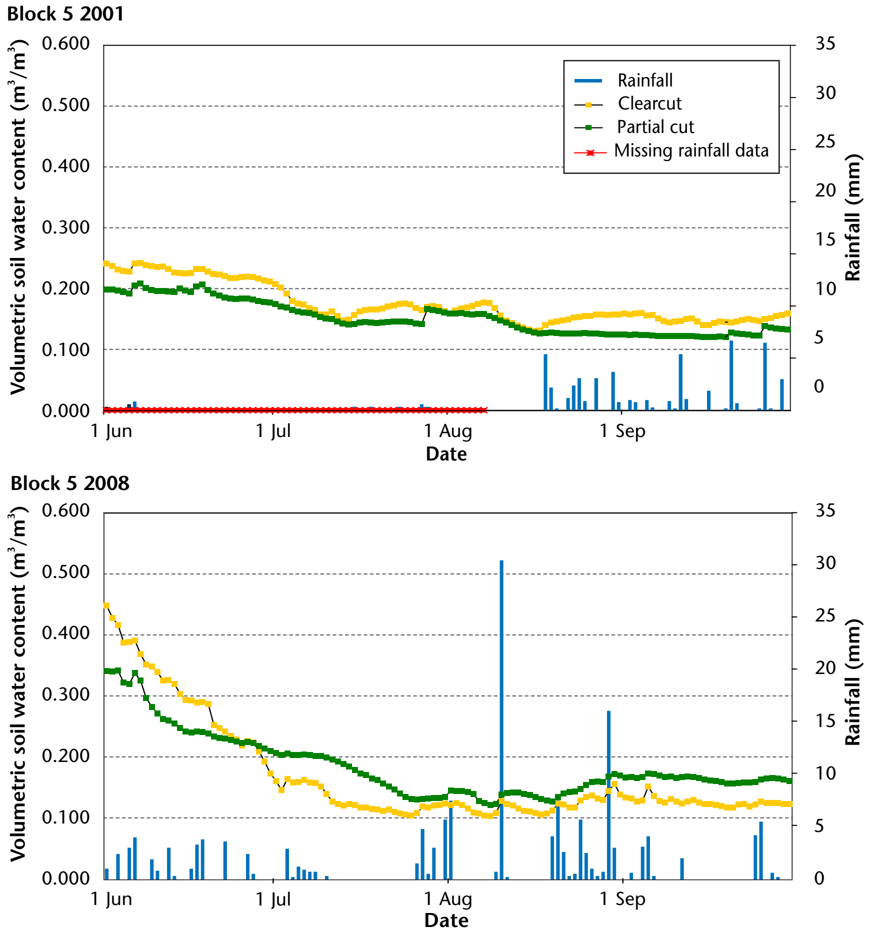


FIGURE 11 *Concluded.*

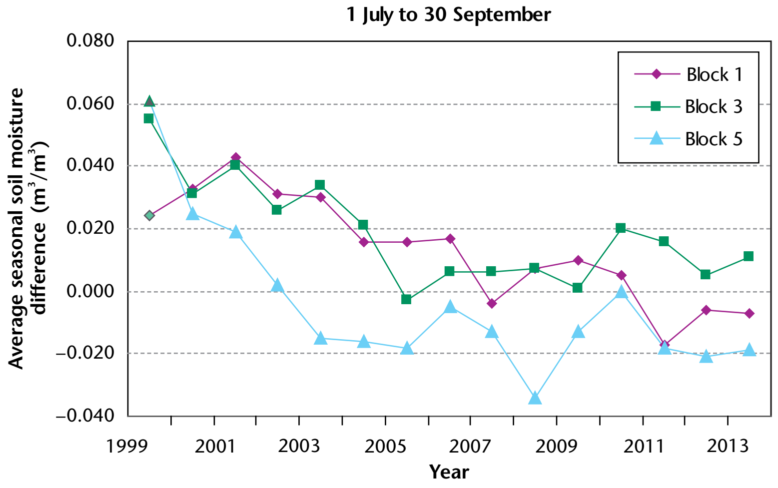


FIGURE 12 *Mean daily difference between 3 cm volumetric soil water content in the clearcut and partial cut treatments for each block over the period 1999–2013. Daily mean differences were averaged from 1 July through 30 September for each year.*

al. (2010) found that height growth of lodgepole pine was approximately 30% greater in the clearcuts than the partial cut openings and diameter growth was 50% greater.

Mortality of the mature lodgepole pine likely contributed to lower water use in the partial cuts after about 2004. Beetle-killed trees may have influenced the soil moisture regime through increased net precipitation after about 2008, when forests in the study area were entering the grey attack phase, and decreased canopy transpirations during the green attack phase (2004–2007), both of which would tend to increase soil moisture in the partial cuts. This finding is consistent with the work of Spittlehouse (2007), Pugh and Gordon (2012), and Pendall et al. (2010) who predicted that mountain pine beetle attack and subsequent death of the mature forest would lead to decreased evapotranspiration and increased soil moisture during the first year after pine beetle infestation (green attack phase). These factors, which would tend to increase soil moisture in the openings, would have been partly offset because of the increased evapotranspiration related to the growth of regeneration and other vegetation species (see Figure 3). The apparent effect of mountain pine beetle on the water balance may be limited by the fact that soil water measurements in the openings were made 5 m from the forest edge and not in the uncut mature forest area of the partial cuts.

Figure 13 compares the seasonal (1 May–30 September) total soil water stress days (days when soil water potential is < –1.0 MPa) for the periods 1999–2003 and 2006–2009. During the 1999–2003 period, there were marginally more soil water stress days in the partial cut blocks, whereas during the 2006–2009 period there were significantly more stress days in the clearcut blocks. The increased use of water in clearcut blocks may be related to the higher growth rates of shrubs, herbs, and regeneration than in the partial cut

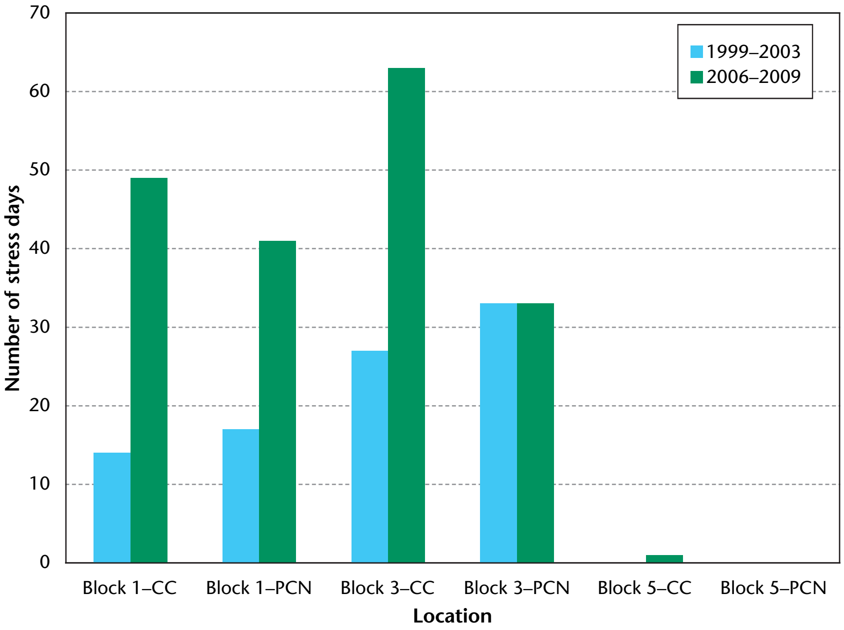


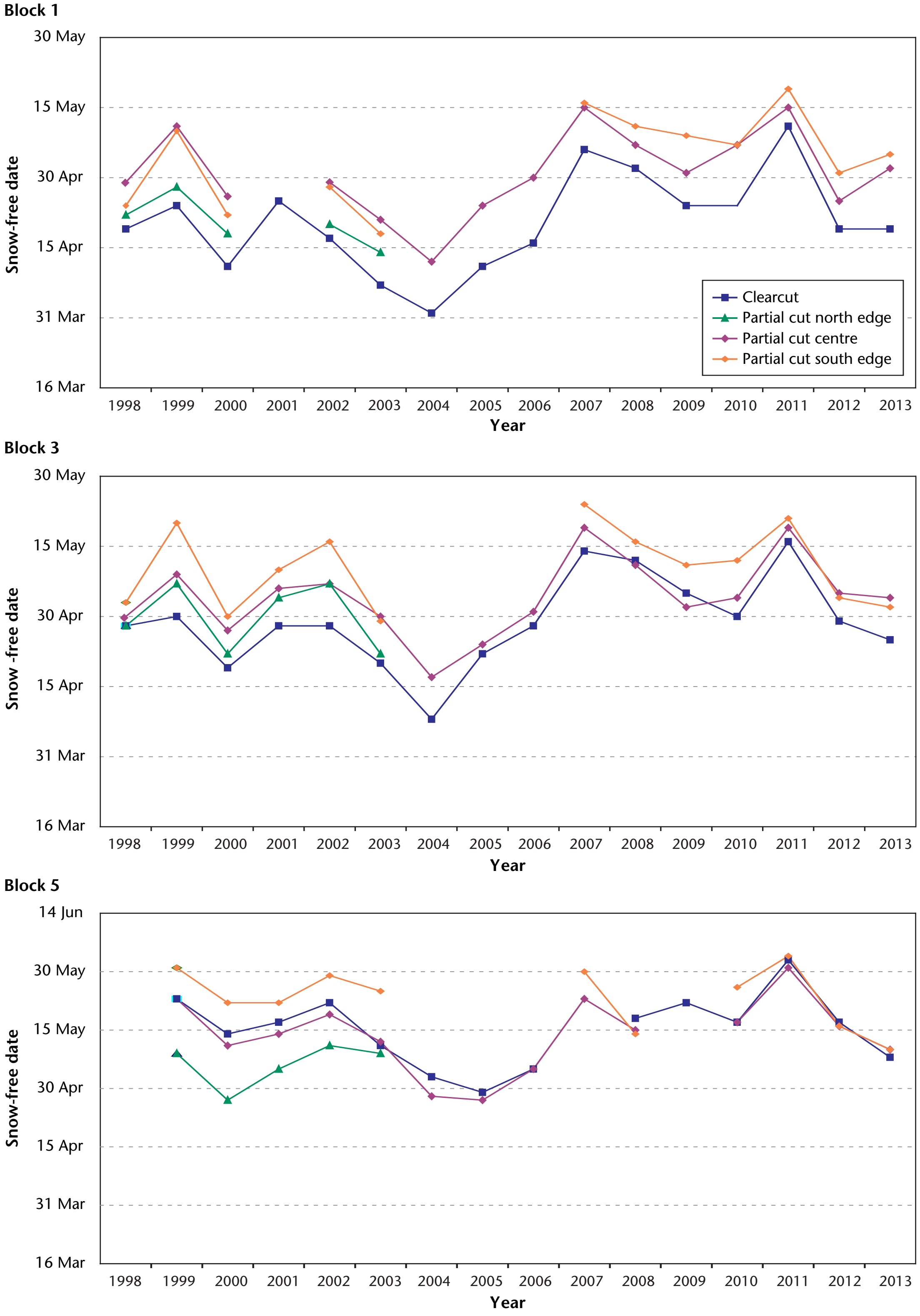
FIGURE 13 *Seasonal (1 May–30 September) total soil water stress days averaged for the periods 1999–2003 and 2006–2009 in the clearcut (CC) and partial cut (north-edge microsite, PCN) for each block. Soil water stress day is defined as a day when the mean soil water potential is less than –1.0 MPa.*

openings. More water may also be available in the partial cut blocks because there is less consumption by the overstorey canopy. Annual growing season soil water stress days are reported for all blocks, treatments, and microsites in Appendix 7.

3.6 Snow-free Dates

Snow-free dates are compared for the clearcuts and partial cut microsites for each year over the period 1998–2013 (Figure 14). Appendix 8 presents the snow-free dates for all blocks, treatments, and microsites. Because of the varying synoptic weather patterns that affect snow accumulation and ablation, it is difficult to draw any conclusions regarding the effect of vegetation regrowth and beetle-caused tree mortality on the inter-annual variations of snow-free date. Nevertheless, the effect of elevation is clear. The snow-free dates at block 5 were 2–3 weeks later than those in blocks 1 and 3. The reasons are the larger snowpacks and slower melting attributed to the lower average air temperatures at higher elevations. Clearcuts generally were snow free a few days earlier than the earliest-melting partial cut block (except at block 5). South-edge (north-facing) microsites were the latest-melting microsites because of the shading from trees to the south.

As new forests grow in the clearcuts and partial cuts, snow-free dates are expected to converge in a fashion similar to soil temperature and minimum air temperature. We can already see evidence of this, especially in blocks 3 and 5. At block 3, the south-edge location typically had a snow-free date that was 1–2 weeks later than the centre position during the years 1998–2010. During the years 2011–2013, only a few days difference in snow-free data was evident between these locations. During the first 4 years of the study at block 5, a wide separation in snow-free dates occurred between the north- and south-edge locations, with intermediate dates at the clearcut and centre locations. During the last 3 years of the study, there is little difference in snow-free dates among the south-edge, centre, and clearcut locations.



Block 1

Block 3

Block 5

FIGURE 14 *Comparison of annual snow-free dates between the clearcuts and the partial cut microsites for the period 1998–2013. These dates were determined using the daily minimum and maximum 1 cm soil temperatures. Snow cover was assumed to be gone when the daily maximum 1 cm soil temperature rose to + 0.5°C or more.*

4 SUMMARY

The fundamental goal of the Itcha-Ilgachuz Project was to test partial cut silvicultural systems as an alternative to clearcuts in maintaining the integrity of caribou habitat. In this report, we compare microclimate conditions in partial cut openings with those in nearby clearcuts in the context of regenerating young forests and dying mature forests.

The patterns observed for STI at all three blocks are similar, with clearcuts accumulating significantly more STI than partial cut locations and, at least initially, south-edge (north-facing) microsites accumulating the fewest STI among the partial cut microsites. Over time, the clearcut and partial cut openings will progress towards a mature forest structure and expectations are that the soil temperature regimes will converge. Some evidence of this occurring was seen over the duration of this study. In addition, during the early years of this study, distinct differences in soil temperature regimes were evident among the different microsites in the partial cut openings (Sagar et al. 2005). These differences are diminishing over time as regeneration and other vegetation layers develop in the openings. The snow-free date, which is partly controlled by large-scale synoptic weather patterns, explained 37% (range: 9–54%) of the variance in annual totals of STI.

Frequent, and sometimes severe, growing season frosts on these study blocks were common in the first part of the study period (Sagar et al. 2005). In the later part of the study, the overall frequency of frost events declined in both clearcut and partial cut treatments. Partial cut openings lowered the frequency and severity of growing season frosts compared to the clearcuts in the earlier part of the study; however, the differences diminished in the later part of the study period. Frequencies and overall severity of growing season frosts are expected to decrease to similar levels in both the partial cut opening and clearcuts as the forest regrows. These trends were seen in the data beginning around 2008. Also, conditions within the partial cut openings at the different microsites are homogenizing, with the centre locations experiencing similar frequencies of frost to edge locations. The higher rainfall, and probably cloudier conditions, in the 2004 and 2005 growing seasons likely contributed to markedly low frost frequencies.

Changes to soil moisture regimes attributed to human-caused disturbances such as clearcut logging are well documented. Mature forests intercept more precipitation and also tend to have higher water use than new clearcuts (Spittlehouse 2006). In the early years of this study, soil volumetric water content (θ_v) in the clearcuts was consistently higher than that in the partial cut openings, but the differences trended down through time. By 2013, θ_v in the clearcuts was less than in the partial cuts at blocks 1 and 5, and close to zero in block 3. Between 1999 and 2013, the difference between the elevated θ_v levels in the clearcuts and those in the partial cut openings decreased with time, and in fact was reversed at block 5 (i.e., higher θ_v in the partial cut openings). This change appears to be driven by the faster rate of regeneration growth in the clearcuts and possibly the loss of mature forests around the partial cut opening related to the mountain pine beetle infestation.

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APPENDIX 1 Growing season (1 May–30 September) mean daily 15 cm soil temperatures (°C), for each block, treatment and microsite from 1997 to 2013. Means and standard deviations are for the period 1999–2013. Exceptions to the data collection periods are footnoted.

	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	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
2004	11.2	10.0	10.2	8.8	11.1	9.4	9.5	8.9	9.9	8.8	8.3	7.4
2005	10.5	9.4	9.4	8.2	10.6	8.3	8.3	8.6	9.8	8.5	8.8	7.4
2006	10.5	9.2	9.0	7.4	9.9	8.1	7.7	7.8	9.2	8.1	7.4	6.5
2007	9.5	8.9	8.4	7.5	8.9	7.8	7.7	7.3	10.1	7.6	7.5	6.4
2008	9.8	8.7	8.2	7.4	9.3	7.9	7.8	7.7	8.7	7.8	7.5	6.4
2009	10.7	9.4	8.8	7.9	9.9	8.4	8.0	8.2	9.1	10.3	10.2	8.6
2010	10.1	9.0	8.4	7.6	9.4	8.1	7.8	7.8	8.2	7.9	7.7	6.0
2011	9.0	8.4	7.6	7.2	8.3	6.9	6.9	7.0	7.1	6.8	6.9	5.4
2012	10.1	8.9	8.3	7.9	9.3	7.6	7.6	8.0	8.2	8.3	8.0	6.4
2013	11.2	10.3	9.1	9.2	10.6	9.0	8.9	9.4	9.0	9.3	9.1	7.6
Mean	10.1	9.0	8.6	7.7	9.5	8.1	7.9	7.8	8.5	7.8	7.5	6.4
SD	0.8	0.6	0.6	0.6	0.8	0.6	0.6	0.7	0.8	0.8	0.8	0.7

▨ Highlighted data not used in calculations of mean and standard deviation.

Notes:

A correction was applied to soil temperatures if offset was > 0.1°C.

1997 Blocks 1 and 3: monitoring began on 5 June (i.e., no data 1 May–4 June).
1997 Blocks 1 and 3, partial cuts: no data for centre position 5 June–1 July.
1998 Block 3, partial cut: missing data 8 August–3 November.
1998 Block 5, partial cut: data collection began on 28 May (i.e., no data 1 May–27 May).
1999 Block 1, clearcut: missing data 17–27 September.
2000 Block 1, partial cut: bad data 30 April–2 June; corrected for missing data using linear regression.
2001 Block 1, partial cut, north and south edges and centre: missing data 27 April–18 May; corrected for missing data using linear regression.
2003 Block 3, partial cut, north edge: sensor failed on 4 June so no data.
2004 Block 3, partial cut: mean soil temperature was not calculated for the centre position because of missing data; for the north-edge position, mean soil temperature was based on a regression with the south-edge position for the 12-day period 27 July–7August.
2004 and 2005 Block 1 clearcut: only rep. 2 was used in calculation.
2005 Block 3 partial cut: changing pattern from microsites may be related to blowdown near the sensor microsites.
2007 Block 5 clearcut: missing data, 1 May–3 June.
2009 Block 5 partial cut: missing data 1–27 May.
2013 Stations were dismantled on 26 September 2013, so totals not based on complete month.

APPENDIX 2 Growing season (1 May–30 September) total 5°C soil temperature index from 1997 to 2013. Soil temperature index based on 15 cm soil temperatures for each block, treatment, and microsite. Means and standard deviations are based on the period 1999–2013. Exceptions to the data collection periods are footnoted.

	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	616	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
2004	951	785	811	631	946	692	710	639	767	600	569	499
2005	847	692	699	542	866	530	540	606	753	547	606	457
2006	874	698	655	461	801	555	503	515	706	551	450	382
2007	775	639	598	476	678	511	500	474	605	498	502	359
2008	780	622	572	456	622	512	501	508	659	509	480	338
2009	897	709	644	544	791	598	551	584	738	636	628	447
2010	810	646	579	483	711	514	487	519	592	504	484	334
2011	697	594	503	471	609	437	424	458	491	432	456	275
2012	803	659	576	542	716	490	490	544	593	602	560	406
2013	933	791	642	661	844	624	612	672	641	665	650	476
Mean	811	659	618	498	742	549	525	520	632	515	495	373
SD	102	65	71	73	94	62	66	75	88	83	90	70

▨ Highlighted data not used in calculations of mean and standard deviation.

Notes:

1997	Blocks 1 and 3: monitoring began on 5 June (i.e., no data 1 May–4 June).
1997	Blocks 1 and 3, partial cuts: no data for centre position 5 June–1 July.
1998	Block 3, partial cut: missing data 8 August–3 November.
1998	Block 5, partial cut: data collection began on 28 May (i.e., no data 1 May–27 May).
1999	Block 1, clearcut: missing data 17–27 September; probably no more than 25 missing growing degree days; estimated missing growing degree days: north edge and centre < 10 and south edge 0.
2000	Block 1, partial cut: bad data 30 April–2 June; estimated missing soil temperature indices based on previous year's data.
2001	Block 1, partial cut, north and south edges and centre: missing data 27 April–18 May.
2003	Block 3, partial cut, north edge: sensor failed on 4 June so no data; value estimated by regression with centre using previous year's data.
2004 and 2005	Block 1 clearcut: only rep. 2 was used in calculation.
2005	Block 3 partial cut: changing pattern from microsites may be related to blowdown near the sensor microsites.
2007	Block 5 clearcut: missing data, 1 May–3 June.
2009	Missing data 1–27 May; probably fewer than 10 missing soil temperature indices.
2013	Stations were dismantled on 26 September 2013, so totals not based on complete month.

APPENDIX 3 Total frost events and severe frosts for the season (1 June–15 August) and for July of each year from 1997 to 2013. Based on daily minimum 15 cm air temperature (°C) at each block, treatment and microsite. Means and standard deviations are for the period 1999–2013.

Block 1

	Severe frosts (< –4 °C)								Total frosts (< 0 °C)							
	Clearcut		Partial cut (north edge)		Partial cut (centre)		Partial cut (south edge)		Clearcut		Partial cut (north edge)		Partial cut (centre)		Partial cut (south edge)	
Year	Season	July	Season	July	Season	July	Season	July	Season	July	Season	July	Season	July	Season	July
1997	11	2	6	0	3	1	5	0	41	15	25	8	12	8	21	6
1998	6	1	2	1	2	1	2	1	24	5	12	2	15	3	11	2
1999	17	6	5	0	5	0	5	0	40	18	27	10	29	12	24	8
2000	9	0	2	0	2	0	2	0	34	11	19	4	23	6	21	4
2001	10	2	5	0	5	0	5	0	46	14	27	6	37	10	30	8
2002	16	5	6	2	7	3	6	2	51	20	31	10	43	14	37	15
2003	9	0	3	0	6	0	3	0	45	16	28	10	39	13	31	10
2004	10	0	2	0	2	0	2	0	29	8	19	3	22	5	18	3
2005	8	3	1	0	1	0	1	0	40	19	22	9	34	17	20	9
2006	11	2	1	0	1	0	1	0	41	9	32	6	37	7	37	7
2007	10	4	0	0	1	1	1	1	47	13	28	8	38	12	35	12
2008	11	4	1	0	3	1	2	1	52	21	40	15	46	18	44	17
2009	16	2	7	1	9	1	7	1	45	10	32	6	37	6	37	6
2010	17	6	6	2	7	3	6	2	45	16	33	13	32	13	34	13
2011	8	2	3	1	3	1	3	1	38	9	29	5	34	7	32	5
2012	4	1	0	0	1	0	0	0	38	12	28	8	28	8	28	8
2013	3	1	1	0	1	0	1	0	27	16	19	10	22	12	19	11
Mean	11	3	3	0	4	1	3	1	41	14	28	8	33	11	30	9
SD	4	2	2	1	3	1	2	1	7	4	7	3	8	4	9	4

APPENDIX 3 Continued

Block 3

	Severe frosts (< −4°C)								Total frosts (< 0°C)							
	Clearcut		Partial cut (north edge)		Partial cut (centre)		Partial cut (south edge)		Clearcut		Partial cut (north edge)		Partial cut (centre)		Partial cut (south edge)	
Year	Season	July	Season	July	Season	July	Season	July	Season	July	Season	July	Season	July	Season	July
1997	6	1	2	0	0	0	3	0	26	9	10	2	4	2	22	6
1998	1	1	0	0	0	0	1	1	14	3	8	1	9	1	12	2
1999	5	1	3	0	3	0	3	0	26	10	18	4	19	4	22	7
2000	6	0	0	0	1	0	2	0	30	5	16	1	19	1	25	3
2001	9	1	2	0	2	0	7	1	40	13	24	4	28	7	32	8
2002	9	3	2	1	4	3	7	1	41	15	23	9	25	10	35	10
2003	8	2	2	0	2	0	2	0	42	19	18	7	21	8	27	12
2004	6	0	1	0	2	0	2	0	26	6	12	1	13	2	14	2
2005	5	2	0	0	0	0	0	0	38	17	9	3	13	5	21	8
2006	7	1	1	0	1	0	1	0	36	7	18	3	29	6	33	8
2007	4	2	0	0	1	1	1	1	44	14	15	4	27	7	31	11
2008	8	3	0	0	2	0	5	2	47	21	26	11	33	16	39	18
2009	7	1	4	1	6	1	7	1	33	7	24	4	26	4	32	6
2010	6	3	4	2	6	4	7	4	29	10	25	12	29	12	29	12
2011	1	1	0	0	0	0	0	0	36	9	23	5	33	9	38	12
2012	1	0	1	0	1	0	1	0	26	8	24	7	26	7	29	8
2013	1	0	0	0	0	0	0	0	17	8	14	6	18	6	21	10
Mean	6	1	1	0	2	1	3	1	34	11	19	5	24	7	29	9
SD	3	1	1	1	2	1	3	1	8	5	5	3	6	4	7	4

APPENDIX 3 Continued

Block 5

	Severe frosts (< −4 °C)								Total frosts (< 0 °C)							
	Clearcut		Partial cut (north edge)		Partial cut (centre)		Partial cut (south edge)		Clearcut		Partial cut (north edge)		Partial cut (centre)		Partial cut (south edge)	
Year	Season	July	Season	July	Season	July	Season	July	Season	July	Season	July	Season	July	Season	July
1997	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
1998	–	–	0	0	1	1	1	1	–	–	10	3	11	3	11	3
1999	11	7	3	0	4	1	5	1	35	14	20	7	22	8	23	9
2000	11	1	0	0	1	0	1	0	41	8	25	3	28	4	27	4
2001	20	5	5	1	6	1	5	1	56	18	33	7	36	8	37	8
2002	14	6	3	0	3	0	3	0	53	21	25	9	30	9	28	8
2003	15	4	3	0	3	0	3	0	58	23	16	3	27	11	20	6
2004	11	0	2	0	2	0	2	0	47	17	13	1	17	2	16	2
2005	12	5	0	0	0	0	0	0	47	21	15	7	22	9	19	9
2006	22	4	1	0	2	0	2	0	51	17	17	2	23	4	20	3
2007	6	2	0	0	0	0	0	0	35	12	14	3	18	5	19	5
2008	18	11	0	0	0	0	0	0	52	19	27	10	33	14	29	12
2009	7	2	1	0	1	0	1	0	43	11	19	2	27	4	26	4
2010	12	5	2	1	4	3	3	2	50	20	22	8	18	10	21	7
2011	2	1	0	0	0	0	0	0	38	10	19	6	26	9	22	9
2012	5	1	0	0	1	0	1	0	38	15	12	3	18	6	14	3
2013	2	2	0	0	0	0	0	0	36	20	10	5	18	10	17	7
Mean	11	4	1	0	2	0	2	0	45	16	19	5	24	8	23	6
SD	6	3	2	0	2	1	2	1	8	5	6	3	6	3	6	3

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

Notes:

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

APPENDIX 4 Extreme air temperatures for the season (1 June–15 August) and July of each year from 1997 to 2013. Based on daily minimum 15 cm air temperatures (°C) at each block, treatment, and microsite. Exceptions to the data collection periods are footnoted.

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
2004	–7.8	–3.3	–5.3	–2.5	–6.0	–2.9	–5.4	–2.3
2005	–5.9	–4.8	–4.7	–3.3	–4.6	–3.7	–4.3	–3.3
2006	–9.7	–6.4	–5.6	–3.5	–6.5	–3.8	–6.0	–3.6
2007	–6.0	–6.0	–3.6	–3.6	–4.3	–4.3	–4.1	–4.1
2008	–8.2	–6.4	–5.5	–3.8	–5.8	–4.1	–5.6	–4.1
2009	–10.9	–9.5	–7.8	–6.5	–7.9	–6.7	–8.0	–6.6
2010	–9.3	–8.2	–6.9	–6.0	–7.1	–6.1	–7.1	–6.1
2011	–7.1	–5.9	–4.7	–4.2	–5.1	–4.2	–4.9	–4.4
2012	–5.5	–4.6	–3.8	–3.4	–4.3	–3.4	–3.8	–3.3
2013	–5.7	–4.3	–4.1	–2.9	–4.4	–3.0	–4.2	–3.0
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
2004	–7.0	–2.8	–4.0	–0.6	–4.8	–1.3	–5.3	–1.3
2005	–4.7	–4.4	–1.9	–1.9	–2.3	–2.1	–3.1	–3.1
2006	–8.5	–5.6	–4.2	–2.6	–6.1	–3.3	–6.2	–3.8
2007	–5.4	–5.4	–3.0	–3.0	–4.5	–4.5	–4.5	–4.5
2008	–5.4	–5.1	–3.8	–3.2	–4.5	–4.0	–5.3	–4.5
2009	–7.8	–6.4	–6.2	–4.9	–6.9	–5.9	–7.2	–6.1
2010	–7.6	–7.6	–6.2	–6.2	–6.6	–6.5	–6.8	–6.8
2011	–4.0	–4.0	–3.1	–3.1	–3.4	–3.3	–3.8	–3.4
2012	–4.0	–2.3	–4.1	–2.2	–4.2	–2.4	–4.4	–2.6
2013	–4.4	–2.2	–3.3	–3.3	–3.4	–3.4	–3.8	–3.8
Extreme	–9.2	–7.8	–6.2	–6.2	–6.9	–6.5	–7.2	–6.8

APPENDIX 4 Continued

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
2004	−8.4	−3.5	−5.1	−0.6	−5.8	−0.8	−5.6	−0.7
2005	−7.0	−6.6	−2.8	−1.6	−3.3	−2.2	−3.1	−2.0
2006	−9.7	−8.7	−4.7	−2.7	−6.2	−4.0	−5.5	−3.3
2007	−6.3	−5.7	−2.3	−1.8	−2.6	−2.4	−2.9	−2.9
2008	−8.4	−8.4	−2.8	−2.4	−3.7	−3.1	−3.8	−2.9
2009	−7.2	−6.3	−4.2	−2.2	−5.1	−2.5	−5.1	−2.2
2010	−9.2	−9.2	−5.7	−5.7	−6.5	−6.5	−6.3	−6.3
2011	−4.6	−4.6	−2.5	−2.5	−2.9	−2.9	−3.3	−3.3
2012	−5.1	−3.9	−3.9	−1.2	−4.0	−1.7	−4.4	−1.6
2013	−4.6	−4.6	−2.0	−1.1	−2.3	−2.0	−2.8	−1.7
Extreme	−10.4	−9.2	−6.8	−5.7	−7.4	−6.5	−7.1	−6.3

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

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

APPENDIX 5 Growing season (1 May–30 September) mean daily minimum air temperature for 1997–2013. Based on 15 cm air temperatures (°C) for each block, treatment, and microsite. Means and standard deviations are for the period 1999–2013. Exceptions to the data collection periods are footnoted.

	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	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
2004	–0.5	0.8	0.2	0.8	–0.3	2.9		1.8	–1.7	1.5	0.8	1.1
2005	–1.8	–0.2	–0.8	–0.4	–1.3	1.3	0.9	0.0	–2.2	0.7	0.2	0.6
2006	–2.5	–0.6	–1.2	–0.9	–1.7	0.8	–0.2	–0.7	–2.9	0.5	–0.1	0.7
2007	–2.5	–0.6	–0.9	–0.6	–1.1	1.0	0.0	0.0	–1.3	0.9	0.6	0.6
2008	–2.2	–0.8	–1.1	–1.0	–1.4	0.5	–0.4	–0.6	–1.9	0.8	0.2	0.4
2009	–2.6	–0.9	–1.2	–1.1	–1.1	0.4	–0.2	–0.3	–1.2	1.9	1.2	1.4
2010	–2.2	–0.9	–1.1	–1.1	–0.8	0.1	–0.4	–0.3	–1.4	0.4	0.3	0.5
2011	–1.4	–0.1	–0.3	–0.2	–0.3	0.7	0.1	0.0	–0.4	1.0	0.5	0.7
2012	–2.1	–0.6	–0.8	–0.6	–0.2	0.3	–0.1	–0.4	–1.1	1.0	0.7	0.8
2013	–0.6	0.6	0.4	0.5	0.8	1.3	0.9	0.6	–0.5	1.7	1.2	1.3
Mean	–2.1	–0.5	–0.9	–0.6	–1.0	0.8	0.1	–0.1	–1.7	0.6	0.3	0.6
SD	0.7	0.6	0.6	0.6	0.8	0.7	0.4	0.6	0.8	0.6	0.5	0.3

▨ Highlighted data not used in calculations of mean and standard deviation.

Notes:

1997 Blocks 1 and 3: monitoring began on 5 June (i.e., no data 1 May–4 June).
1997 Blocks 1 and 3, partial cuts: no data for centre position 5 June–1 July.
1998 Block 3, partial cut: missing data 8 August–3 November.
1998 Block 5, partial cut: data collection began of 28 May (i.e., no data 1 May–27 May).
1999 Block 1, clearcut: missing data 17–27 September.
2000 Block 1, partial cut: bad data 30 April–2 June; corrected for missing data using linear regression.
2001 Block 1, partial cut, north and south edges and centre: missing data 27 April–18 May; corrected for missing data using linear regression.
2003 Block 3, partial cut, north edge: sensor failed on 4 June so no data.
2004 Block 3, partial cut: mean soil temperature was not calculated for the centre position because of missing data; for the north-edge position, mean soil temperature was based on a regression with the south-edge position for the 12-day period 27 July–7August.
2004 and 2005 Block 1 clearcut: only rep. 2 was used in calculation.
2005 Block 3 partial cut: changing pattern from microsites may be related to blowdown near the sensor microsites.
2007 Block 5 clearcut: missing data, 1 May–3 June.
2009 Block 5 partial cut: missing data 1–27 May.
2013 Stations were dismantled on 26 September 2013, so totals not based on complete month.

APPENDIX 6 Seasonal total rainfall (mm) in block 1, 3, and 5 clearcuts for 2000–2013. Exceptions to the data collection periods are footnoted.

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	96.8[b]	112.2[b]	31 May–6 October
2004	259	244	306	29 May–21 October
2005	197	253	328	27 May–11 October
2006	75	92	116	24 May–30 September
2007	149	131[c]	247	4 June–29 September
2008	126	103	153	28 May–1 October[d]
2009	71	83	169	28 May–27 September
2010	103	3[e]	124	2 July – 30 September
2011	95.5[f]	146	224.5	15 June–25 September
2012	22[g]	39[g]	114	9 June–25 September
2013	127	154	212	28 May–25 September

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

b 2003 Blocks 3 and 5: Rain gauges significantly out of level on 15 August 2003 site visits; undetermined amount of rainfall lost.

c 2007 Missing data 1 July–9 August.

d 2008 Block 1: Except 25 May.

e 2010 Missing data mid-July–30 September.

f 2011 Missing data about mid-August–25 September.

g 2012 Block 1: Missing data about late June–6 September; block 3: missing data from about 17 July–26 September.

APPENDIX 7 Total number of water stress days over the growing season (1 May–30 September) for 1999–2013. Water stress based on soil water potential of less than –1.0 MPa for each block and treatment; the soil water potential was measured at the north-edge locations of the partial cuts only. Exceptions to the data collection periods are footnoted.

	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[a]	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
2004	1	0	14	1	146	34	131	104	5	0	0	0
2005	153	72	20	0	153	10	136	153	6	0	0	0
2006	57	52	49	13	73	47	0	0	22	4	15	0
2007	8	10	18	8	29	23	0	0	0	0	0	0
2008	40	60	76	73	99	95	61	71	3	0	0	0
2009	89	73	87	71	94	87	62	60	0	0	0	0
2010	61	66	57	59	99	89	136	137	67	34	26	22
2011	43	40	35	35	51	51	93	48	21	0	0	77
2012	58	77	65	70	75	79	75	76	69	32	44	132
2013	71	69	66	64	27	37	81	79	120	26	70	104
Mean	36	37	42	32	59	46	56	50	21	6	10	22

⬜ Highlighted cells indicate that sensors may be at the end of the life, as readings may be too high given the amount of rainfall recorded.

🟩 Highlighted cells indicate that stress days were not counted between 1 May and 22 or 23 May because of failing soil moisture blocks; blocks were replaced 22 or 23 May.

[a] 1999–All sites: Soil moisture monitoring did not begin until 29 June; since it was a wet year, no stress days were missed.

APPENDIX 8 Annual snow-free dates based on 1 cm soil temperatures for each block, treatment, and microsite for 1998–2013

	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)
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
2004	🟩 01 Apr	–	🟩 12 Apr	–	🟩 08 Apr	–	🟩 17 Apr	–	03 May	–	28 Apr	–
2005	11 Apr	–	24 Apr	–	22 Apr	–	24 Apr	–	🟩 29 Apr	–	🟩 27 Apr	–
2006	16 Apr	–	30 Apr	–	28 Apr	–	01 May	–	05 May		05 May	–
2007	06 May	–	🟦 15 May	16 May	14 May	–	🟦 19 May	🟦 24 May		–	23 May	30 May
2008	02 May	–	07 May	11 May	12 May	–	11 May	16 May	18 May	–	15 May	14 May
2009	24 Apr	–	01 May	09 May	05 May	–	02 May	11 May	22 May	–	–	–
2010	24 Apr	–	07 May	07 May	30 Apr	–	04 May	12 May	17 May	–	17 May	26 May
2011	🟦 11 May		🟦 15 May	🟦 19 May	🟦 16 May		🟦 19 May	21 May	🟦 02 Jun		🟦 31 May	03 Jun
2012	19 Apr		25 Apr	01 May	29 Apr		05 May	04 May	17 May		16 May	16 May
2013	19 Apr		02 May	05 May	25 Apr		04 May	02 May	08 May		10 May	10 May
Mean	20 Apr	20 Apr	1 May	4 May	29 Apr	30 Apr	4 May	11 May	15 May	6 May	14 May	24 May

🟦 Highlighted cells represent latest snow-free date.

🟩 Highlighted cells represent earliest snow-free date.