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Climate and Its Relevance to Lodgepole Pine Performance at the Sub-Boreal Bednesti Research Site over a 30-year Period (EP0995)

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Robert M. Sagar, Jean L. Heineman,
and Lorne Bedford

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ABSTRACT

The Bednesti site preparation study, located in the SBSdw3 biogeoclimatic variant of central British Columbia, examined lodgepole pine response to various types of site preparation from 1988–2017. In addition to tree measurements, climate and microclimate data were collected to characterize important environmental parameters such as air temperature, soil temperature, soil moisture, precipitation, and solar radiation that could assist with the interpretation of pine survival and growth responses. Although various publications have sometimes referred to the climate and microclimate data to help interpret specific tree or vegetation responses, no single publication has focussed on the environmental data or comprehensively examined possible correlations with tree growth. Although it is difficult to draw firm conclusions regarding such relationships due to limited replication of some of the climate and microclimate measurements, trends can be identified that suggest avenues for further research.

In this report, we examine the overall climate record at the Bednesti research site for the 30-year period from 1988–2017, focussing on mean air temperature and precipitation. Combined data from the Bednesti site and a nearby Environment and Climate Change Canada (ECCC) station indicate that extreme minimum air temperature dropped below -35°C every winter during the first decade of the study (1988–1997), and during 5 of those 10 years, it dropped to -40 °C or lower. In contrast, during the following two decades (1988–2017), annual extreme minimum air temperature reached -35°C in only 8 of 20 years (40% of the time) and reached -40°C only once. Notably, in 2015, the annual extreme minimum air temperature at Bednesti reached only -22.1°C. This trend is typical of the temperature conditions that allowed the mountain pine beetle to flourish in the interior of British Columbia. We also observed that years with the highest mean annual temperature were not necessarily those with the highest growing-season temperature; some warmer than average years earned that status more from above-average cold-season temperatures than above-average growing-season temperatures. There were also indications that conditions at Bednesti were becoming drier. Growing-season precipitation was below the 30-year normal for seven of the last nine growing seasons (2009–2017) and the 3-year interval from 2013–2015 featured a combination of warm and dry growing-season conditions not recorded for any other 3-year period during the study.

The most detailed and well-documented microclimate data collected at the Bednesti site were recorded in a disc trench hinge plot during the period 1999–2017. Visual examination of data suggested a correlation between the date when the majority of lodgepole pine height growth was completed in late July to early August and the date when soil water potential (ψ_s) dropped to levels generally considered limiting to plant growth. We lacked sufficient soil moisture data to properly examine the importance of soil moisture deficits to the cessation of annual height growth, but it is a question of interest given the expectation of increasingly warmer, and potentially drier, growing-season conditions in central British Columbia.

During the 1992, 1993, and 1994 growing seasons, lodgepole pine height and diameter growth data were collected at approximately 2-week intervals. While it is beyond the scope of this report to present these results in full, we discuss findings for one of the disc trench hinge treatment plots. In the 3 monitoring years, the majority of height growth (approximately 95%)

was finished between 24 July and 1 August, while the majority of diameter growth was finished between 9 September and 23 September. Diameter growth continued in minor amounts until at least the end of September. In all 3 years, peaks in height and diameter growth coincided with each other, with additional smaller peaks in diameter growth occurring later in the season after the rate of height growth had declined.

In 2012, we began monitoring light and soil moisture below the canopy of an isolated dense stand of trembling aspen that had developed in one of the disc trench hinge pine measurement plots. Both light and soil water availability appear to have been reduced by the aspen overstorey. Growing-season photosynthetically active radiation (PAR) levels beneath the aspen canopy were only 15–20% of those in the open, while soil moisture stress, as indicated by a decline in ψ_s, began 1–2 weeks earlier than in a nearby plot occupied by planted lodgepole pine with no overtopping aspen. At age 25–30 years, lodgepole pine growing under the aspen canopy exhibited height and diameter growth that were approximately 70% and 50%, respectively, of those growing free of aspen competition.

Collecting, maintaining, and evaluating climate and microclimate data that accompany silviculture studies is expensive and time consuming. These data are often regarded as secondary to tree-related data, and management of the associated metadata (i.e., information related to measurement location, data collection intervals, and equipment models, calibration, and maintenance) is commonly neglected. Lack of reliable metadata reduces the usefulness of climate and microclimate data, particularly in studies such as Bednesti that endure for many years. One of our foremost objectives in preparing this Technical Report was to present metadata relating to climate and microclimate data collection at the Bednesti study site, along with information about the extent, completeness, and reliability of data (presented in Appendix 1). We hope that this documentation will facilitate ongoing use of these valuable data sets.

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1 INTRODUCTION

Site preparation is used extensively in sub-boreal and boreal regions of British Columbia to improve conifer seedling survival and early growth through the manipulation of growing conditions at the microenvironmental level. Numerous studies have documented positive responses to site preparation, and, in some cases, the beneficial effects on growth have persisted for more than two decades (e.g., Boateng et al. 2009, 2012). Studies that attempt to identify causal factors related to tree response generally include some type of climate and microclimatic data collection. Although these data are expensive and time consuming to collect, information about diurnal, seasonal, and annual fluctuations in weather and microclimate is extremely useful for interpreting conifer survival and growth responses. Climate and microclimate data are often considered to be of secondary importance in the management of silviculture research projects, however, and, in many cases, are not examined with the same level of intensity as the tree data and not presented as stand-alone results.

In this report, we focus on climate and microclimate data collected over a 30-year period (1988–2017) to accompany a lodgepole pine site preparation study (EP0995) near Prince George. Where possible, despite the inherent difficulty of adequately replicating climate/microclimate data, we identify apparent correlations between lodgepole pine growth responses and trends in monitored climate and microclimatic variables. The efficacy of specific site preparation treatments depends largely on how well they relieve microclimatic limitations to conifer survival and growth. For example, the availability of root zone soil water is an important factor for lodgepole pine seedlings—when they are newly planted, root elongation ceases when soil water potential falls below -0.06 to -0.07 MPa (Grossnickle 2005) and growth during the early years is limited by soil water potentials below -0.2 MPa (Black and Mitchell 1990; Fleming et al. 1994). Under such conditions, scalping, ripping, and herbicide treatments that increase soil water availability through grass removal are effective (e.g., Fleming et al. 1998; Newsome et al. 2016a).

Low soil temperature can likewise limit conifer seedling water uptake and photosynthesis, with a physiological threshold identified at approximately 7°C, below which root resistance to water uptake increases steeply (Running and Reid 1980). On boreal or high-elevation sites where cold, wet soils prevail, successful site preparation treatments are most often those that create better drained, warmer microsites with reduced presence of vegetation that causes physical damage and shading (e.g., Newsome et al. 2016b).

Summer frost is also an important limitation to conifer seedling survival and growth in British Columbia, especially on dry sites that have poor cold air drainage (Steen et al. 1990). Under those conditions, the goal of site preparation is to reduce the frequency of damaging summer frosts by improving the nighttime air temperature regime at seedling height. This is generally accomplished by treatments that expose mineral soil, create raised beds, and/or remove vegetation that traps cold air at seedling height (Spittlehouse and Stathers 1990). These treatments may also slightly enhance daytime air temperature, increasing the amount of time that seedlings are growing within the optimal range of 15–25°C.

The degree to which conifers respond to site preparation also depends on their tolerance of environmental conditions. Of all the conifer species used to regenerate harvested sites in British Columbia, lodgepole pine

(*Pinus contorta* var. *latifolia*) tolerates the broadest range of environmental conditions (Klinka et al. 2000). It has a high tolerance for frost and drought, and tolerates, but does not thrive in, conditions where there is excess moisture. It is among the least shade tolerant of native conifer species (Kobe and Coates 1997; Wright et al. 1998; Claveau et al. 2002) and tends to have rapid juvenile growth rates. These features have resulted in lodgepole pine being widely used as a regeneration species in interior British Columbia during the past three decades, especially in the Sub-Boreal Spruce (SBS) biogeoclimatic zone of the central interior.[1]

In 1988, a number of individual experiments were established at the Bednesti research site to examine lodgepole pine survival and growth responses to various types of site preparation in a dry warm variant of the SBS zone (SBSdw3) (Figure 1). The Bednesti North experiment, which includes a total of nine treatments, is situated north of the access road into the site. A variety of smaller experiments, including the Bednesti Directional Study (aka Bednesti South) that examines specific characteristics of disc trenching treatments, and the Madge study that examines the effects of a fine mixing treatment, are located south of the access road. For all experiments, site preparation treatments were applied in 1987, and planting with lodgepole pine PSB 211 (1+0) seedlings was done in spring 1988. Climate and microclimate data were collected more or less continuously from 1988 to 2017, although the position and sophistication of the monitoring stations and equipment changed over the years. A climate station was erected in 1988

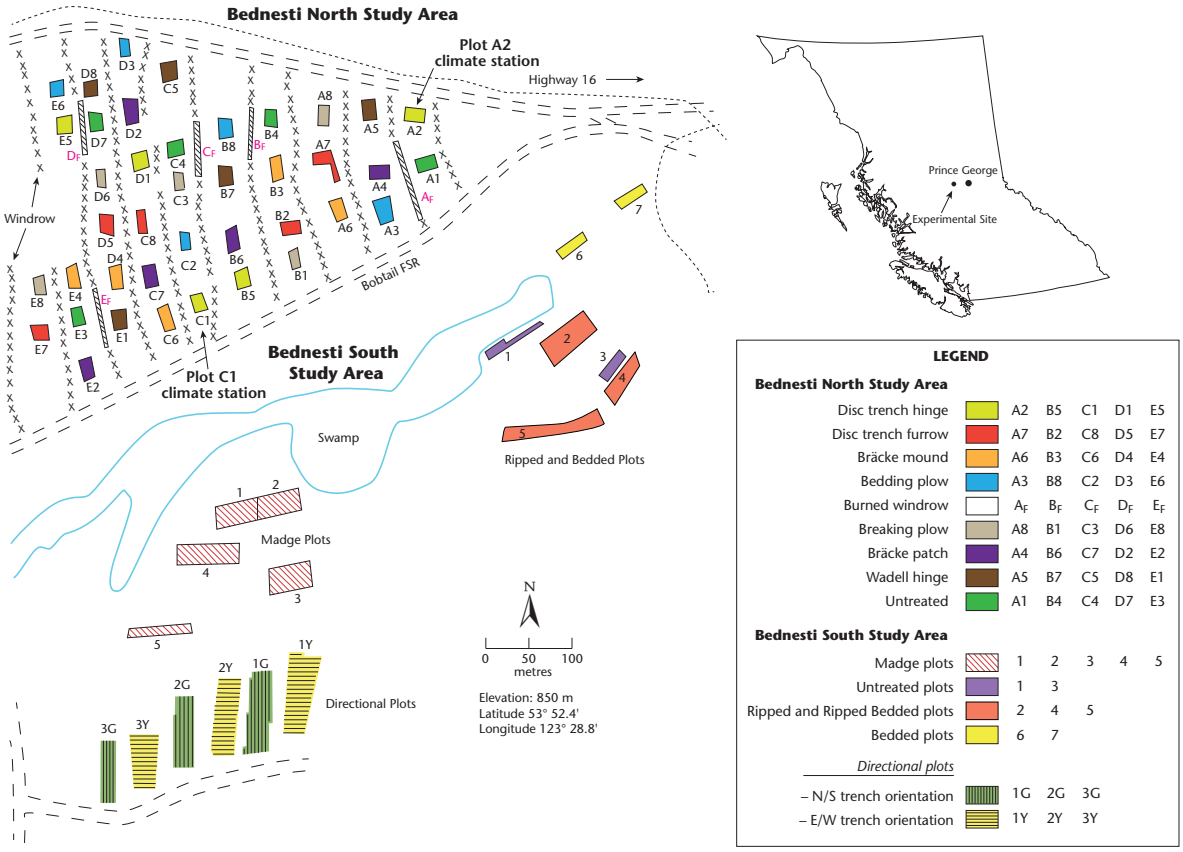

FIGURE 1 *Layout of the Bednesti research site.*

[1] From the B.C. Ministry of Forests, Lands and Natural Resources RESULTS database (Accessed May 2014).

at the start of the study, and dataloggers were installed to examine seedling microenvironments in key treatments. The main body of well-documented climate/microclimate data was collected over the period 1999 through 2017 in a location (plot C1) considered representative of conditions over the majority of the Bednesti North experimental area. Conditions under a localized patch of dense aspen were examined beginning in 2012.

Full treatment descriptions, experimental design information, and lodgepole pine survival and growth results are available in McClarnon et al. (2016) for the Bednesti North and Bednesti South experiments, and in Boateng et al. (2010) for the Madge experiment. Climate results from the Bednesti experiments have never been comprehensively presented. In this report, we present climate and microclimate results for experiments conducted at the Bednesti research site. Although our ability to draw solid conclusions is limited by the lack of complete replication that is characteristic of silviculture experiments, we also examine possible correlations between climate or microclimate data and lodgepole pine growth. The results we present can be roughly divided into two periods that correspond with: (1) establishment and juvenile growth (years 1–11, 1988–1998) and (2) early stand development (years 12–30, 1999–2017).

2 METHODS

2.1 Site Characteristics

The Bednesti study site is located approximately 50 km west of Prince George, B.C. (53° 52′ N, 123° 29′ W, elevation 850 m), in the Stuart variant of the dry warm Sub-Boreal Spruce subzone (SBSdw3) (Delong et al. 1993). The site was strip harvested in 1963–1964, and the remaining strips were removed in 1971. By 1986, the site was insufficiently stocked with juvenile conifers that were growing among the relatively non-competitive low shrub-herb community. Standing juvenile trees were sheared and piled into windrows in winter 1986/87 in preparation for the research study.

Soils are representative of the Deserters soil association (Dawson 1989) and range from Brunisolic Gray Luvisols to Orthic Dystric or Gleyed Orthic Dystric Brunisols (Soil Classification Working Group 1998). Soil textures are predominantly loamy sand or sandy loam (with a minor silt clay loam component) with 10–65% coarse fragments. The effective rooting depth is 10–50 cm. The humus form at the start of the study was a Hemimor (3–6 cm deep with occasional areas of thinner development). Soil samples collected for descriptive purposes from a single untreated control plot when the study began in 1988 indicated that total mineral soil bulk density averaged 1350 and 1770 kg/m^3 at depths of 0–10 and 10–20 cm, respectively.

2.2 Climate and Microclimate Data Collection

This report focusses primarily on climate and microclimate data collected at various locations in the Bednesti North study area; however, data were also collected in relation to experiments in the Bednesti South study area as described in Table 1. While it is beyond the scope of this report to present results for all the climate or microclimate data collected at the Bednesti site since 1988, we would like the forest research community to be aware of its existence and potential for use. Metadata related to each of the climate and microclimate data sets collected from 1988 to 2017 at the Bednesti study area are presented, as fully as possible, in Appendix 1.

TABLE 1 *A description of climate and microclimate metadata presented in Appendix 1*

Data type	Table	Information presented	Time period	Location of data collection
Climate data for the Bednesti study area	TABLE A1-1	Description of equipment, equipment location, and data output	1988–1990	Bednesti South study area
			1992	Unknown
			1993–1997	Unknown
			1998	Unknown
			1999–2017	Bednesti North study area
	TABLE A1-2	Measurement years for individual variables and reliability of data	As described for TABLE A1-1	As described for TABLE A1-1
Microclimate data for the Bednesti North experiment	TABLE A1-3	Description of equipment, equipment location, and data output	1988–1990	Bräcke mound, Bräcke patch, bedding plow, Wadell trenching, and breaking plow treatment plots
			1999–2017	Disc trench hinge (aka Delta hinge) plot C1
			2012–2017	Localized dense aspen patch in plot A2
	TABLE A1-4	Measurement years for individual variables and reliability of data	As described for TABLE A1-3	As described for TABLE A1-3
Microclimate data for the Bednesti South experiments	TABLE A1-5	Description of equipment, equipment location, and data output	1988–1990	Madge (fine mixing) study
				Directional disc trenching study
			1993–1997	Madge (fine mixing) study
				Directional disc trenching study
	TABLE A1-6	Measurement years for individual variables and reliability of data	As described for TABLE A1-5	As described for TABLE A1-5
Microclimate data for the Bednesti North mound temperature study	TABLE A1-7	Equipment description and sensor depth	1997–1998	Between Bednesti North plots B3 and B4

2.2.1 Bednesti site prepared treatment areas 1988–1998 In 1988, 1 year after site preparation treatments were applied, lodgepole pine seedlings were planted on the experimental plots, and climate and microclimate monitoring began. During the period 1988–1998, a series of five different weather station installations (some with multiple dataloggers) was located in either the Bednesti North or Bednesti South study areas. These installations were used to measure basic climate variables, such as air temperature, rainfall, windspeed, and solar radiation, as well as microclimate variables such as soil temperature and soil water potential, in specific treatments. Metadata for these early installations were poorly documented, however, and many of the details relating to sensor type and position, measurement interval, and station location are unknown. Some information was gleaned from data file column headings in data summary files, and, in other cases, it was possible to make educated guesses and inferences (i.e., sensor types may have been presumed to be what was in common usage during that time). Metadata for these sites have been compiled in Appendix 1.

The focal points of our analyses for the 1988–1998 period are the basic seasonal climate variables of air temperature (screen height) and rainfall as they affected seedling survival and growth. These variables were measured somewhere within the Bednesti research area for all or part of every growing season except 1991, although the exact locations of the climate stations are unknown. Very limited field notes and no quality control information are available for these early data. As a means of quality control, the data were

compared with data from nearby Environment and Climate Change Canada (ECCC) stations, and, in some cases, missing data were replaced with or determined from linear regressions with ECCC data (Appendix 2).

Air temperature and relative humidity were measured together using a Campbell Scientific, Edmonton, Alberta, Model 207 sensor for all years from 1988 to 1998, with the exceptions of 1991 (when there was no weather station) and 1992 (data missing). Metadata for the 1988–1990 and 1993 periods confirms that the Model 207 sensors were housed in a Stevenson Screen at a height of 1.05–1.5 m above the ground. A Stevenson Screen was likely also used in 1994–1998, but this is not confirmed by any metadata. Rainfall data were collected using a tipping bucket rain gauge (Sierra Misco Inc., Model 2501) mounted with its collecting funnel top at a height of 60 cm above the ground.

2.2.2 Bednesti North site prepared treatment areas 1999–2017 Weather and microclimate conditions were monitored in and adjacent to disc trench hinge plot C1 of the Bednesti North study area (Figure 1). By 1999, lodgepole pine planted in plot C1 averaged 5.1 m tall, and the plot is hereafter referred to as "reforested." Immediately to the east of plot C1 is a small (~20 x 25 m) oblong-shaped area that was not planted with pine and is hereafter referred to as "open." Weather and microclimate measurements in the reforested and open areas started in 1999 and continued through the 2017 growing season. The open area was maintained free of tall vegetation by periodic brushing that was conducted as deemed necessary up to 2007, and annually thereafter. However, as planted lodgepole pine surrounding the small opening increased in height to approximately 13.8 m tall in 2017 (at a density of 1166 stems/ha), the open area became increasingly shaded. Measurements in the reforested and open areas associated with plot C1 included air temperature, relative humidity, soil temperature, soil water potential, volumetric soil water content, solar radiation, photosynthetically active radiation (PAR), and rainfall (Appendix 1).

Soil measurement positions consisted of vertical profiles of sensors (soil temperature and soil water potential) located at depths of 2.5, 15, and 50 cm beneath the mineral/organic interface in the open area and beneath the undisturbed organic layers located between trenches in the reforested area (reforested, undisturbed positions) (Figure 2). Profiles were replicated three times in each of the open and reforested areas. A further soil measurement position was located in the reforested area, at the hinge position of the disc trench berm (reforested, hinge positions), in mineral soil at the 2.5 cm depth only (replicated three times). Volumetric soil water content was measured only once in each of the reforested and open areas, at a depth of 15 cm. Soil temperatures were measured using twisted and soldered thermocouples constructed of 24 AWG copper-constantan duplex extension wire (Omega Engineering Inc., Laval, Quebec, Model EXPP-T-24S). Thermocouple junctions were coated in epoxy. Soil water potential was measured with gypsum blocks (Campbell Scientific, Model 223). Beginning in 2002, volumetric soil water content was measured using water content reflectometers (Campbell Scientific, Model 615).

Air temperature measurements were made at heights of 1.3 and 3.0 m above the ground in the reforested and open areas. Two measurements were taken at each height, one on either side of the 4x4" treated lumber mast. Sensors were mounted on 3/8"-diameter wood dowels extending 10 cm from the masts. Air temperatures were measured with twisted and soldered 36 AWG copper-constantan (Omega Engineering Inc., Model TG-T-36) fine-wire thermocouples. These sensors were unshielded. In addition to

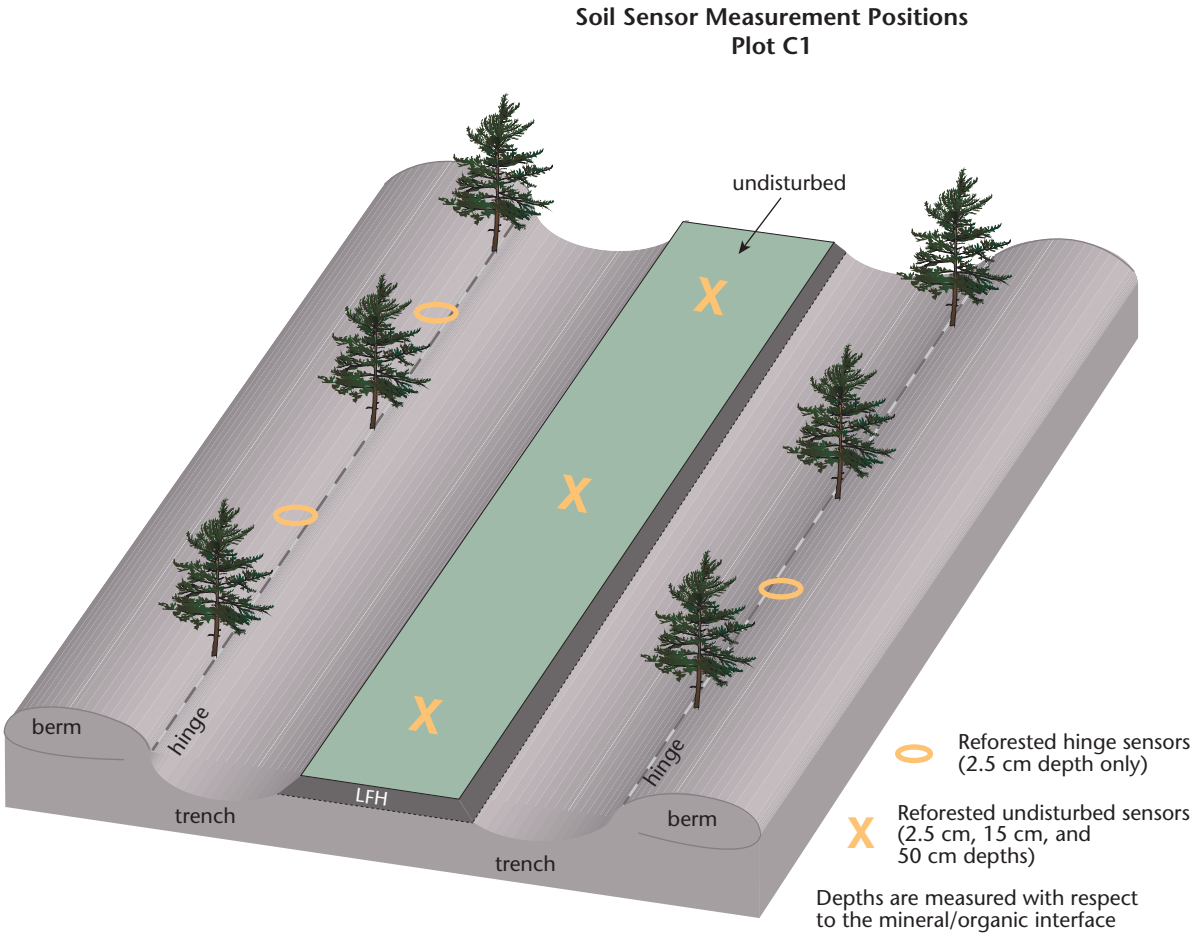

FIGURE 2 *Diagram showing sensor positions in the disc trench hinge treatment of plot C1. In the undisturbed area, organic forest floor (LFH) material overlies mineral soil. Note: This stylized diagram does not distinguish between mineral and organic material in the berm.*

the fine-wire thermocouples, air temperature and relative humidity were measured at a height of 1.3 m at the edge of the open area with a Campbell Scientific, Model HMP35C sensor mounted inside a Gill plate radiation shield (Campbell Scientific, Model 41002).

Solar radiation and PAR were measured at a height of 3 m in the centre of the open area. The sensors were mounted on top of the same 4x4" treated lumber mast where air temperature sensors were mounted. Solar radiation was measured with a silicon pyranometer (Li-Cor Inc., Lincoln, Nebraska, Model LI-200S). PAR was measured with a PARlite quantum sensor (Kipp & Zonen, Delft, the Netherlands) except during the 2012 growing season when the PARlite was removed for calibration and a Li-Cor (Model LI190) quantum sensor was used. Rainfall was measured at the centre of the open area using a tipping bucket rain gauge (Sierra Misco Inc., Berkeley, Calif., Model 2501) mounted on a small wooden platform with its collecting funnel top at a height of 60 cm above the ground.

All data, with the exception of the two water content reflectometers, were collected with a datalogger (Campbell Scientific, Model CR10X- 2MB) and multiplexor (Campbell Scientific, Model AM416) combination. Measurement of the water content reflectometers began in 2002 and their data were logged on a separate Campbell Scientific, Model CR10 datalogger. Dataloggers

and the multiplexor were housed in insulated Pelican cases, which lay on the ground surface and were covered by round, galvanized steel wash tubs. Sensor measurements were made once every five minutes (except soil water potential, which was measured only once every 12 hours). Data recorded included hourly averages, daily average, maximum and minimum, daily total (rainfall only), and daily sample (soil water potential only, at midnight).

The gypsum blocks used to measure soil water potential were initially installed in 1999. These sensors have a maximum useful lifetime of 4–5 years due to dissolution of the gypsum surrounding the electrodes. In 2011, three new gypsum blocks were installed in each of the open and reforested treatments, with an additional two sensors installed in each treatment during 2012. These new sensors were installed at the 15-cm depth only and replaced some of the original (1999) sensors on the multiplexor wiring panel. Due to the limited lifespan of the gypsum blocks, none of the soil water potential data collected between 2004 and 2011 were usable.

2.2.3 Bednesti North aspen stand (Plot A2) 2012–2017 Microclimate monitoring began on disc trench hinge plot A2 of Bednesti North on 30 May 2012 to assess conditions under the dense trembling aspen that had developed in a localized area following disc trenching. Abundant suckering is a typical response of aspen root systems to mechanical disturbance (Haeussler et al. 1990). Measurements of soil water potential were replicated four times using gypsum blocks (Campbell Scientific, Model 227). Volumetric soil water content was measured at one location only using a water content reflectometer (Campbell Scientific, Model 616). Both soil water potential and volumetric soil water content were measured at a depth of 15 cm beneath the mineral/organic interface (the organic layer thickness ranged from 5 to 8 cm). Rainfall was measured with a tipping bucket rain gauge (Texas Electronics, Dallas, Texas, Model 525mm) in a semi-open area just outside plot A2 until the rain gauge was removed in May 2016. In May 2013, a quantum sensor (Kipp & Zonen, Model PARlite) was installed on a post at a height of 1 m above the ground to measure PAR beneath the aspen canopy. Data were collected with a datalogger (Campbell Scientific, Model CR10X-2MB). Measurements were taken every 5 minutes with daily average, maximum, and minimum recorded for all parameters except rainfall (daily totals only). Hourly samples of soil water potential and soil volumetric water content were recorded along with hourly averages of PAR.

2.3 Tree Measurements Relevant to the Presentation of Weather and Microclimate Data (1988–2017)

Lodgepole pine height and diameter in the Bednesti North experiment were measured in early fall after height growth was complete at intervals from 1988 to 2017 (age 30), according to methodology described by McClarnon et al. (2016). The tree measurement results presented in this report utilize lodgepole pine growth data for disc trench hinge treatment plots C1 and A2 for time periods that correspond with the presentation of weather and microclimate data.

In addition to the annual measurements, in 1992, 1993, and 1994, seasonal lodgepole pine growth was assessed in a subset of treatments (100 seedlings per treatment) by measuring trees at approximately 2-week intervals during the growing season (refer to Appendix 3 for exact dates). At the end of each 2-week interval, height was measured from the ground to the base of the terminal bud and diameter was measured at ground level. Height and diameter growth were calculated for each of the growth intervals. Data were collected for the treatments noted in Appendix 3, but only disc trench hinge results are presented in this report.

Aspen presence was assessed in plot A2 when lodgepole pine were 10 years old (1997) in 2-m radius subplots around four randomly selected lodgepole pine. Within each subplot, aspen trees were counted to determine density and the height of the five tallest aspen trees was measured as a means of describing the overall height of the aspen canopy (i.e., canopy height as represented by dominant stems). In 2011 and 2017 (lodgepole pine ages 24 and 30), average aspen canopy height in plot A2 was estimated based on the height of the three tallest aspen trees in 2-m radius subplots around each of nine randomly selected lodgepole pine. Lodgepole pine in plot A2 were assessed as to whether or not they were overtopped by trembling aspen at age 25 (2012). Mean survival and height were calculated separately for overtopped and non-overtopped pine for the purpose of examining the effects of an understorey environment on lodgepole pine performance.

3 RESULTS AND DISCUSSION

3.1 Climate 1988–2017

Figure 3 compares mean annual screen height air temperature for the Bednesti research site with that of the Vanderhoof ECCC station over the period 1988–2017. Data for calculating mean annual temperature were available for only a limited number of years at Bednesti; however, the year-to-year pattern was well correlated with that at the Vanderhoof ECCC station (adjusted $R^2 = 0.956$). Due to the higher elevation of the Bednesti site, mean annual temperatures were typically 1–1.5°C lower than those at the Vanderhoof ECCC station. Mean annual temperatures at Bednesti ranged from 1°C in 1996 to a maximum of 4.5°C in 2015. According to the World Meteorological Organization,[2] the years 2015, 2016, and 2017 were the 3 warmest years on record globally at the time of this writing; however, some areas of northwestern North America had temperatures below normal for 2017, which is reflected in the mean annual temperature at Vanderhoof for

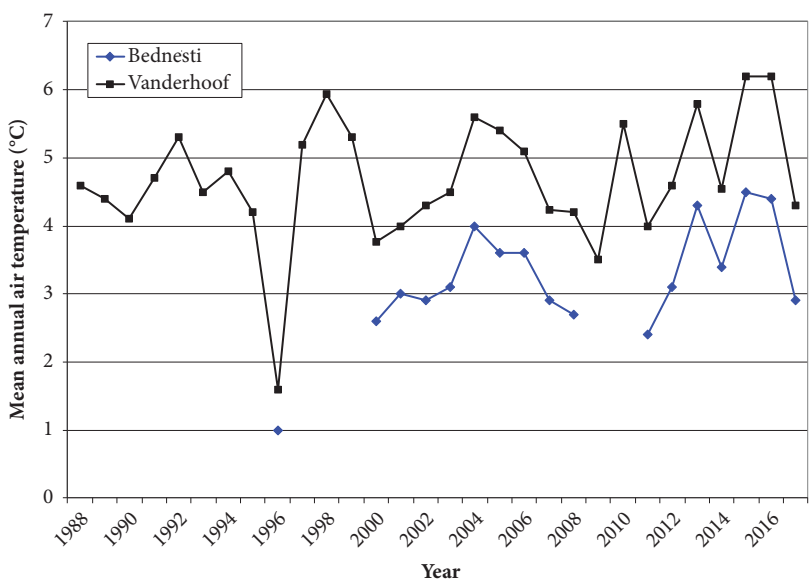

FIGURE 3 *Mean annual air temperature at the Bednesti study site and the Vanderhoof ECCC station for the period 1988–2017.*

[2] World Meteorological Organization, Press Release No.18-01-2018. Available at: https://public.wmo.int/en/media/press-release/wmo-confirms-2017-among-three-warmest-years-record (Accessed 27 February 2018).

that year. The 1996 mean annual temperature at Bednesti was notably cooler than any other year during the 30-year monitoring period. This is consistent with published information indicating that 1996 was a cool year throughout northern British Columbia (Egginton 2005).

Seasonal mean minimum (December–February) and maximum (June–August) air temperatures for the period 1988–2017 at Bednesti and the Vanderhoof ECCC station are presented in Figure 4. At the Vanderhoof station, both the highest (-6.1°C in 1992) and lowest (-17.2°C in 1993 and -17.4°C in 1996) winter mean minimum temperatures occurred during the 1990s; however, overall for the 1989–2017 period, there appears to have been a slight trend of increase in winter mean minimum air temperatures. Excluding 1992, the warmest seasonal minimum air temperature at the Vanderhoof ECCC station was -8.2°C in 2016.

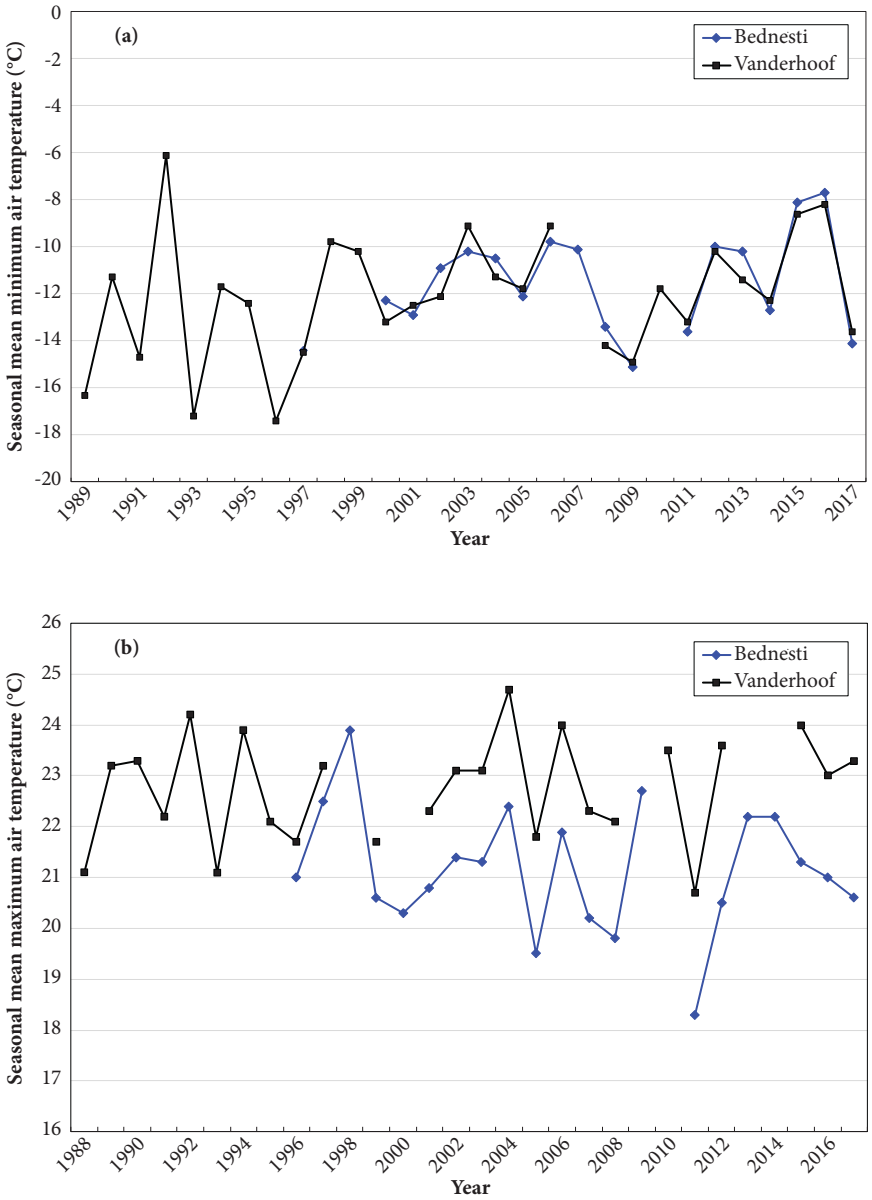

FIGURE 4 *Seasonal mean air temperatures at the Bednesti study site and the Vanderhoof ECCC station for the period 1988–2017: (a) December–February daily mean minimum and (b) June–August daily mean maximum air temperatures.*

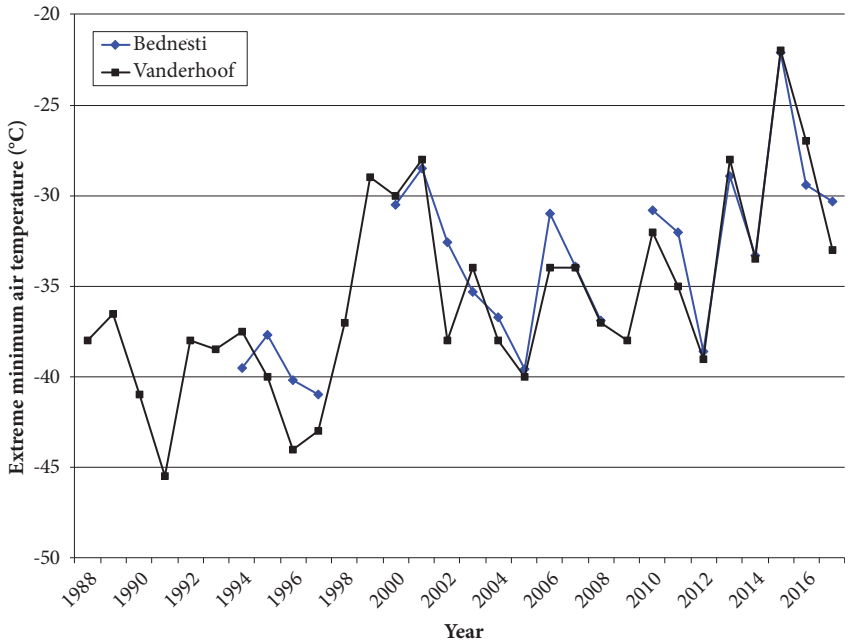

FIGURE 5 *Annual extreme minimum air temperature at the Bednesti study site and the Vanderhoof ECCC station for the period 1988–2017.*

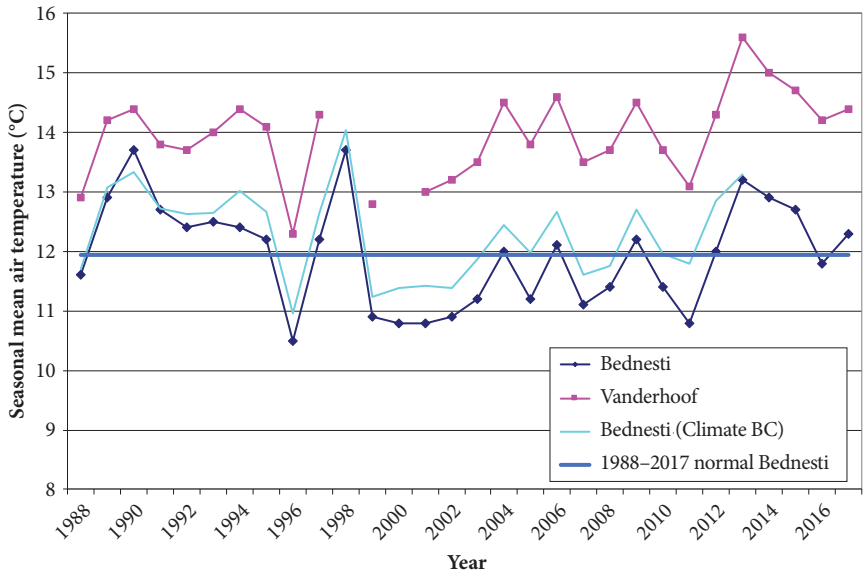

FIGURE 6 *Measured seasonal (May–September) mean air temperature (at a height of 1.3 m) for the Bednesti study site and the Vanderhoof ECCC station compared with modelled air temperature for the Bednesti site based on output from ClimateBC for the period 1988–2017.*

Summer maximum air temperatures at Bednesti ranged from 18 to 24°C between 1988 and 2017, but there does not appear to have been any particular trend of increase or decrease. Annual extreme minimum air temperatures for the period 1988–2017 at Bednesti (where data were available) and the Vanderhoof ECCC station are shown in Figure 5. After 1997, the annual extreme minimum air temperature at Vanderhoof reached -40°C in only one year and failed to go below -30°C in 6 years. For the 10-year period prior to 1998, annual extreme minimum temperature reached at least -35°C every year and was -40°C or lower in 5 of the 10 years. In

2015, the annual extreme minimum air temperature was only -22.0°C at Vanderhoof and -22.1°C at Bednesti. This is the temperature regime that allowed the mountain pine beetle to flourish in the British Columbia interior (Safranyik and Carroll 2006).

Figure 6 shows mean growing-season (May–September) screen height air temperatures at the Bednesti site for the period 1988–2017. To provide validation for the Bednesti record, which included multiple weather stations during the 1988–1998 period, mean measured air temperatures at the Vanderhoof ECCC station and ClimateBC[3] modelled mean air temperatures for the Bednesti location are also included in the figure. The year-to-year pattern of measured seasonal mean air temperatures at Bednesti are mirrored by those at the Vanderhoof ECCC station and those generated by ClimateBC. Growing-season mean air temperatures at Bednesti were generally above the 30-year normal for the period 1988–1998, below to near normal for the period 1999–2012, and above normal for the period 2013–2017. At the Bednesti site, the warmest growing seasons were 1990 and 1998, when the mean air temperature was 13.7°C, while the coolest was 1996 when the mean temperature was 10.5°C. The 5-year period from 1999 to 2003 was notable for consistently having growing-season air temperatures that were below normal. It is interesting to note that years with the highest mean annual temperature (Figure 3) are not necessarily those with the highest growing-season mean temperatures. For example, although 2015 (along with 2016) was the warmest year in terms of mean annual temperature during the 30-year monitoring period at Vanderhoof (and by extension likely at Bednesti as well), the 2015 growing season was only the sixth warmest at Bednesti. The year 1992 represented a relative peak in mean annual temperature, but a relative minimum in growing-season mean temperature. This indicates that 1992 and 2015 earned their status as warm years due more to warmer cold-season temperatures than to warmer growing-season temperatures.

Figure 7 shows frost-free periods (based on air temperature at a height of 1.3 m above ground) at the Bednesti site from 1988 to 2017. The frost-free periods varied from more than 120 days to less than 40 days. The longest frost-free periods were recorded during the intervals 1988–1991 and 2012–2017; in other years, the frost-free periods were typically between 40 and 80 days. It should be noted, however, that the determination of frost-free periods is very sensitive to even small measurement errors. An error of only a few tenths of a degree can make the difference between recording a mid-summer frost, thereby halving the frost-free period, or conversely, not recording a frost and doubling the frost-free period. The large number of years that had relatively short frost-free periods indicates that frost is fairly common during the summer months at the Bednesti site; however, most of these frosts featured temperatures no lower than -2°C. Although hard frost events (air temperature < -4°C) can cause severe damage to conifers (Delucia and Smith 1987) including some species of pine (Lundmark and Hällgren 1987), lodgepole pine in central British Columbia consistently exhibits a high degree of frost tolerance, with low mortality and only some damage at minimum air temperatures of -4 to -8°C (Steen et al. 1990). Lodgepole pine at Bednesti were not damaged by the relatively minor summer frost events at that site, and LePage and Coates (1994) likewise reported that lodgepole pine seedlings were undamaged by growing-season frost events where temperatures dropped as

[3] ClimateBC and the companion program ClimateWNA use the interpolation of existing climate data along with elevation corrections to estimate climate variables at any point in western North America. Available at http://cfcg.forestry.ubc.ca/projects/climate-data/climatebcwna/ (Accessed 18 December 2017).

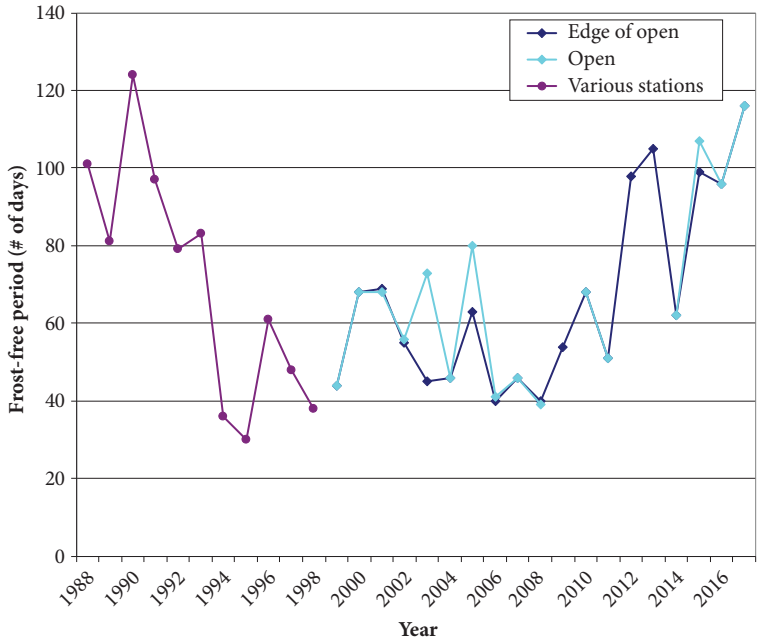

FIGURE 7 *Frost-free period at the Bednesti study site determined using air temperature (at a height of 1.3 m) for each growing season from 1988 to 2017. For the period 1988–1998, data were collected at various climate stations (presumably in open conditions although definitive metadata are lacking) as described in Appendix 1; for the period 1999–2017, data were collected at the centre and edge of the opening adjacent to plot C1.*

low as -5°C in west-central British Columbia. On the high-elevation Chilcotin Plateau of south-central British Columbia, where growing-season daily minimum air temperatures are commonly lower than -4°C, with extremes as low as -12°C, Sagar et al. (2005) and Sagar and Waterhouse (2015) also observed good survival and growth of naturally regenerated lodgepole pine.

Figure 8a shows total growing-season (May–September) precipitation at the Bednesti site for each year from 1988 to 2017. The 30-year normal for the period was 235 mm. Growing-season precipitation was highest in the

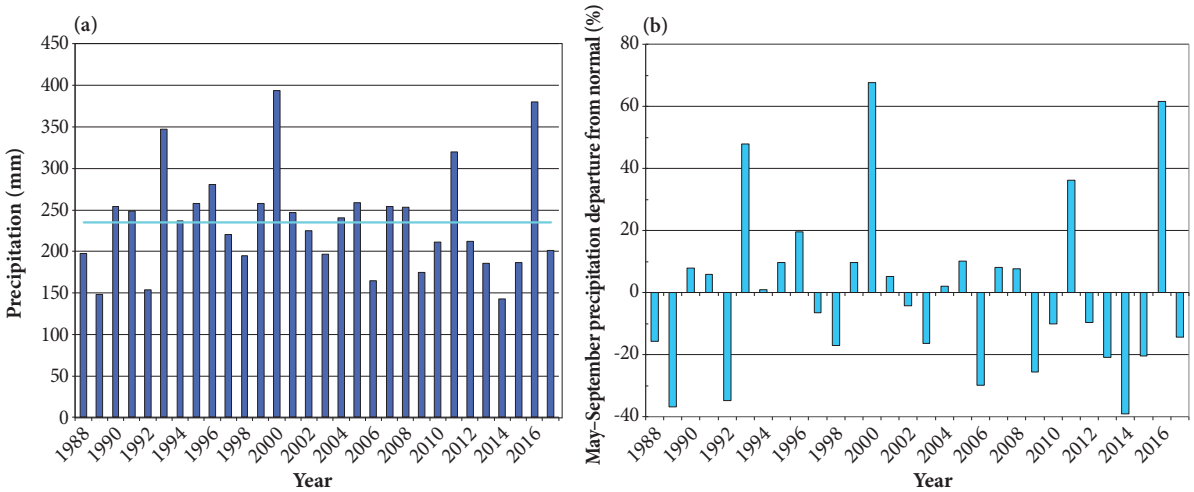

FIGURE 8 *Growing-season (May–September) (a) total precipitation, where the horizontal line is the 30-year normal for the measurement period and (b) percent departure of total precipitation from the 30-year normal at the Bednesti study site for the period 1988–2017. Missing data were replaced by data from the Vanderhoof ECCC station.*

year 2000 (394 mm). It was also over 300 mm in 1993, 2011, and 2016. The 348 mm that fell during the 1993 growing season may have contributed to the high rate of western gall rust infection observed that year among the 6-year-old lodgepole pine at Bednesti (Reich et al. 2015). The lowest total growing-season precipitation occurred in 2014 (143 mm), and this was followed closely by precipitation of approximately 150 mm in the 1989 and 1992 growing seasons. Figure 8b shows the percent departure of seasonal total May–September precipitation from the 30-year normal for each growing season. Four seasons had total precipitation that was more than 20% above the normal and seven seasons had totals that were more than 20% below the normal. It is an interesting temporal trend that seven of the last nine growing seasons (2009–2017) had below-normal growing-season precipitation, with four of those seasons being 20% or more below normal. The greatest deficit occurred in 2014 when growing-season precipitation was 39% below normal.

Cold-season precipitation was not measured at the Bednesti research site, but it is a variable of interest in relation to annual trends in total precipitation. We used the Vanderhoof ECCC station cold-season precipitation as a proxy for the Bednesti site, which is reasonable since winter precipitation tends to be associated with large-scale weather systems affecting large geographic areas. Figure 9a shows the total annual cold-season (October–April) and growing-season (May–September) precipitation for Vanderhoof during the period 1988–2017. Normal (1981–2010) cold-season precipitation was 257 mm, which is only 22 mm more than the mean growing-season precipitation recorded at the Bednesti site. This suggests that growing-season and cold-season precipitation are roughly equal at Bednesti. Note that the published 1981–2010 normal was used for Vanderhoof cold-season precipitation in lieu of the 1988–2017 average because there were significant missing data after 2014. Cold-season precipitation at the Vanderhoof ECCC station was generally above normal for the period 1990–1999, below normal for the period 2000–2010, and normal to above normal for the period 2011–2017. In Figure 9b we combine the percent departures from normal of total

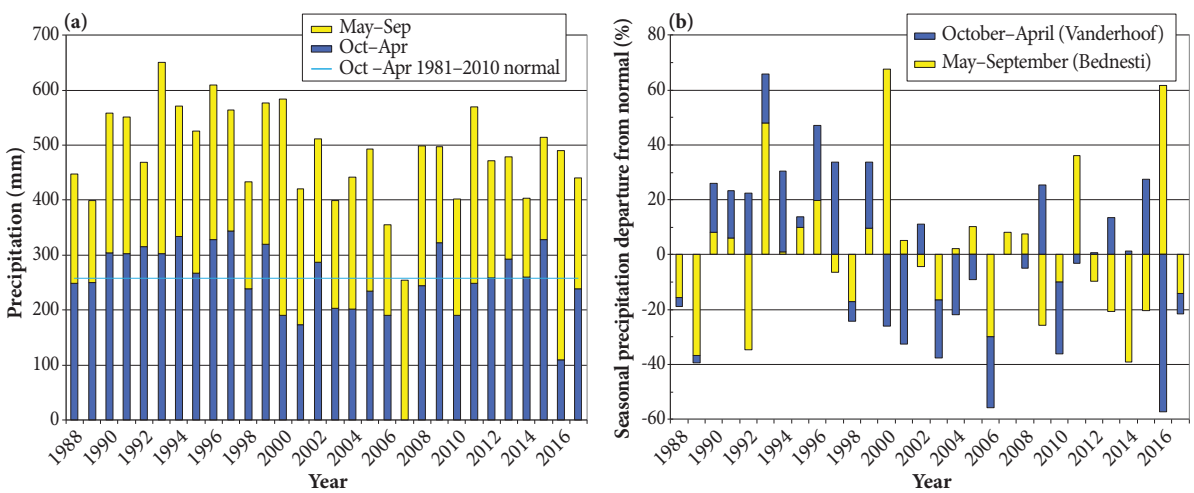

FIGURE 9 *Cold-season (October–April at the Vanderhoof ECCC station) and growing-season (May–September at the Bednesti study site) (a) total precipitation, where the horizontal line is the 1981–2010 cold-season normal derived from ECCC Canadian Climate Normals for the Vanderhoof ECCC station (climate ID 1098D90) and (b) percent departures of total precipitation from the normals for the period 1988–2017. The plotted year corresponds to the year of the growing season following the winter. Note: there was considerable missing data for the years 2007 (64 days), 2014 (29 days), 2015 (32 days), and 2016 (26 days).*

cold-season precipitation at the Vanderhoof station and growing-season precipitation at the Bednesti site. During the decade 2001–2010, low winter precipitation and near normal to below normal growing-season precipitation combined to make it a drier than normal period at the Bednesti site. There were several years (e.g., 2003, 2006, 2010) that had substantial growing- and cold-season precipitation deficits; in 2006, the combination resulted in a deficit of more than 50% relative to the 30-year normal.

3.2 Microclimate 1999–2017

3.2.1 Soil temperature For plot C1, we calculated total soil growing degree-days (GDDs) using a soil temperature threshold of 5°C for the period 1999–2017 (Figure 10). Twenty to 70% more GDDs accumulated in the open area than in the reforested undisturbed area at the same depth, and soil closer to the surface accumulated more GDDs than soil at greater depth. Soil at the 2.5 cm reforested hinge position accumulated somewhat more GDDs than soil at positions that were 2.5 cm beneath the organic layer in areas undisturbed by the trenching process. This is probably because the undisturbed location was overlain by an insulating layer of organic matter, and the reforested hinge position was not.

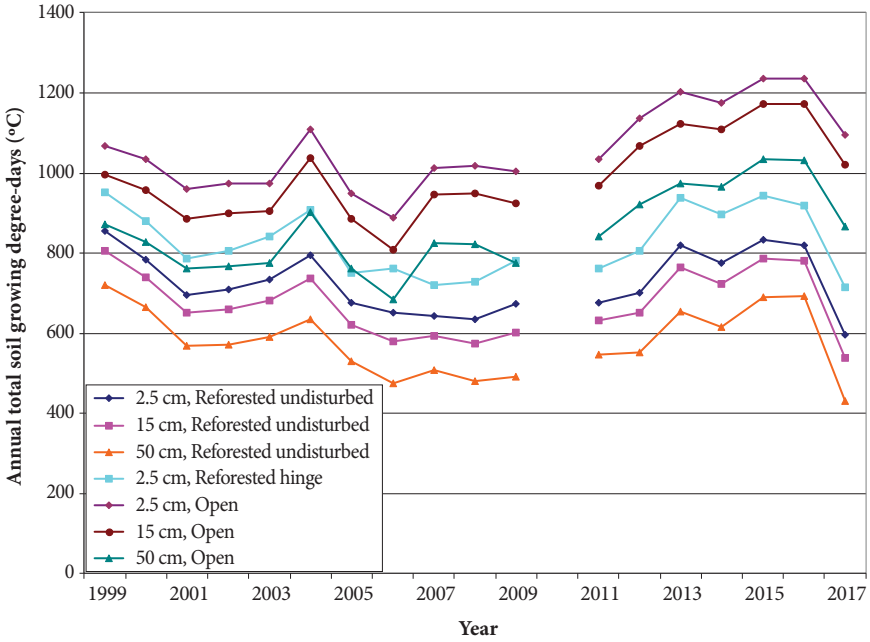

FIGURE 10 *Annual totals of 5°C soil temperature growing degree-days (GDDs) at various depths in reforested undisturbed, reforested hinge, and open locations for the period 1999–2017.*

A range of factors may explain the observed pattern in annual GDD totals for soils in the open location. These could include inter-annual variation in air temperature and solar radiation, rainfall, soil moisture content, and the depth and duration of snow cover during the previous winter. It is likely that trends in annual GDD total are affected by a combination of these factors rather than being highly correlated with any one of them. During the period of 1999–2017, annual GDD totals for the open location were highest from 2013 to 2016, which generally corresponds to above normal growing-season mean air temperatures (except 2016). A similar pattern of annual GDD fluctuation was observed in the reforested location; however, the highest

GDD totals occurred in 1999, with a slight general decline until the warmer period of 2012–2016. We attribute this slight decline to the diminishing amount of solar radiation that reached the forest floor as the lodgepole pine increased in height and crown closure. As a result of the increasing canopy closure, the magnitude of the difference in annual soil GDD accumulations between the open and reforested areas increased steadily from 1999 to 2017 (Figure 11). At Bednesti, we doubt that the slightly cooler soil temperatures that accompanied canopy closure had a negative effect on lodgepole pine growth. Although low soil temperature affects the growth and vigour of seedlings by hampering root uptake of water and nutrients, thereby decreasing photosynthetic ability (Running and Reid 1980; Delucia 1986; Lajzerowicz et al. 2004), growing-season soil temperatures at Bednesti rarely dipped below 5°C, which is the threshold at which water uptake (Kozlowski and Pallardy 1997) and root elongation (Wolken et al. 2011) become limited.

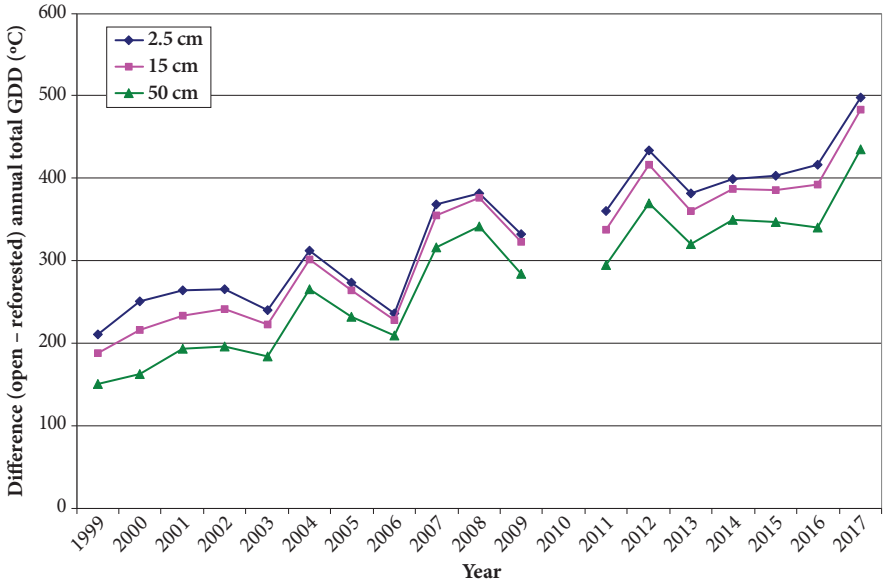

FIGURE 11 *Differences in annual totals of 5°C soil temperature growing degree-days (GDDs) between open and reforested locations at depths of 2.5 cm, 15 cm, and 50 cm during the period 1999–2017.*

3.2.2 Soil moisture Lodgepole pine is tolerant of soil moisture deficits (Klinka et al. 2000); however, seedling root elongation is limited by soil water potentials below -0.06 to -0.07 MPa (Grossnickle 2005) and reductions in early growth can occur when soil water potentials drop below -0.2 MPa (Black and Mitchell 1990; Fleming et al. 1994). We have too few data to determine whether soil moisture deficits that could have affected seedling growth occurred during the first decade after lodgepole pine were planted at Bednesti (1988–1998). From 1999 to 2017, however, as the lodgepole pine canopy gradually closed, it is evident that soil moisture deficits did occur.

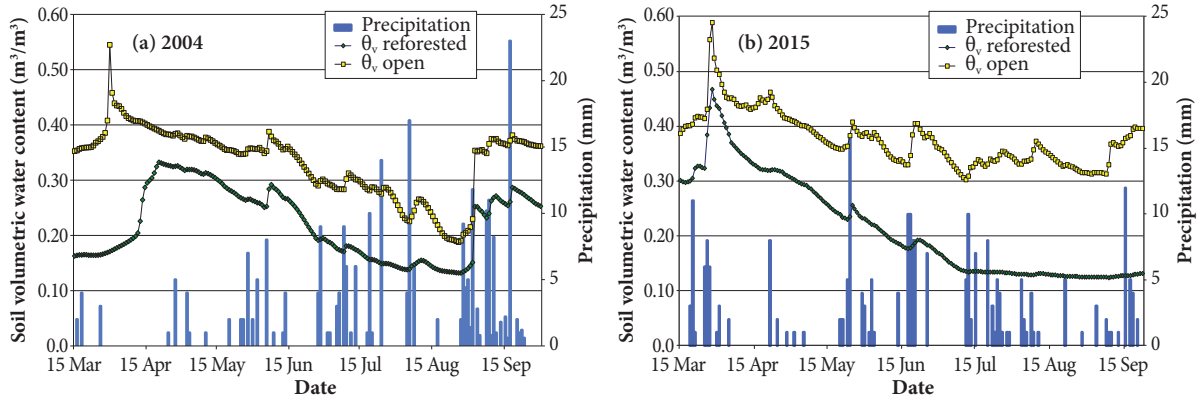

FIGURE 12 *Daily soil volumetric water content (θ_v) at a depth of 15 cm in open and reforested areas along with daily precipitation for representative years (a) 2004 and (b) 2015.*

Figure 12 shows representative seasonal plots of daily soil volumetric water content (θ_v) in the open and reforested locations during the years 2004 and 2015, along with precipitation measured in the open. The characteristic seasonal pattern consists of high θ_v values occurring during the spring snowmelt period of March and April, followed by a general decline throughout the growing season. The first part of the decline is presumed to be due to gravity drainage from the soil profile, and the latter part to the withdrawal of water through evapotranspiration. Soil water content rose in response to rainfall events during the growing season. We also observed that soil water content in the reforested area was consistently lower than that in the open area, and that the difference in seasonal (June–September) mean values increased with time between 2002 and 2017 (R^2=0.391, Figure 13). We think that the observed divergence in θ_v values between the open and reforested areas may be due to increasing interception of precipitation as the lodgepole pine crown closed and canopy volume expanded, and possibly also to increasing water use by the pine. Spittlehouse (2006) reported that

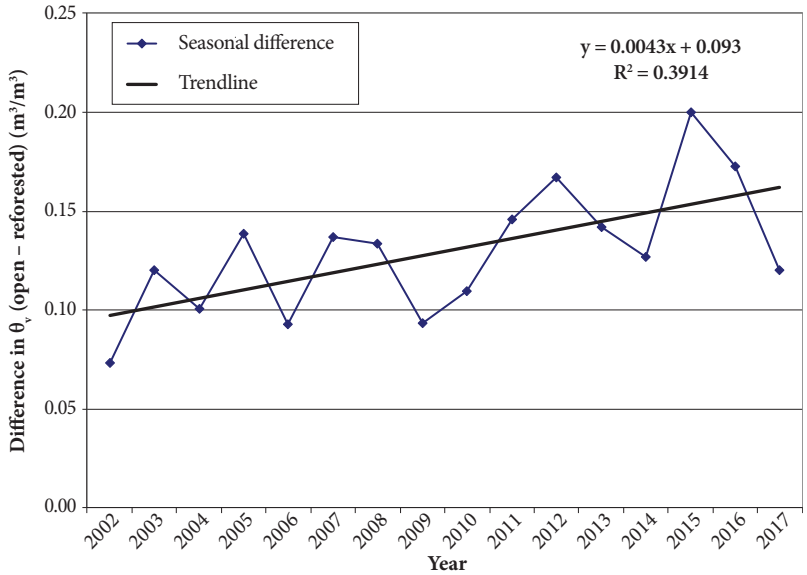

FIGURE 13 *Seasonal (June–September) difference in mean volumetric soil water content (θ_v) between the open and reforested locations for the period 2002–2017 with a linear trend line shown.*

approximately 20% of incoming rain and snow was intercepted by the canopy of a mature high-elevation stand that included lodgepole pine, Engelmann spruce (*Picea engelmannii*), and subalpine fir (*Abies lasiocarpa*). We emphasize that the observed trends at Bednesti are based on only one sensor in each of the open and reforested areas, and that soil moisture can be highly variable spatially; nonetheless, subjective observation during field visits confirmed that soils in the open area were noticeably moister than those in the reforested area by late summer. In contrast to the reforested area, water use in the open area at Bednesti remained relatively constant with time, except for variations due to seasonal weather patterns.

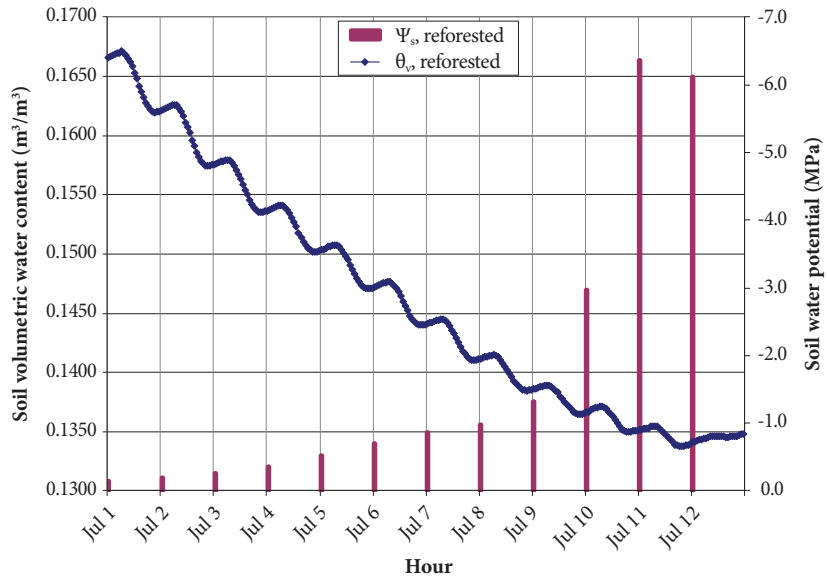

FIGURE 14 *Plot showing hourly soil volumetric water content (θ_v) and daily soil water potential (ψ_s) measured in the reforested area over the period 1–12 July 2015. Note that vertical gridlines represent midnight.*

We also observed an interesting diurnal cycle in growing-season hourly θ_v data that are illustrated for the representative period of 1–12 July 2015 in Figure 14. During each 24-hour period, the value for θ_v declined during the day, which we attribute mainly to tree roots extracting water from the rooting zone in response to evapotranspiration (ET), and then increased at night. It is unlikely that capillary rise is responsible for the nighttime increase in θ_v; we observed the increase over a range of water contents from field capacity to near the wilting point, whereas capillary rise tends to occur at high water contents and diminish as pores become air filled (Hillel 1980), especially in coarse-textured soils such as those at Bednesti. Instead, we think that hydraulic redistribution (or hydraulic lift) may be primarily responsible for the slow rise of θ_v at night. Hydraulic redistribution is the passive movement of water along a water potential gradient, through the root system from wetter to drier soil layers (Prieto et al. 2011). This process would not occur during the day when actively transpiring tree canopies lower water potential in the plants below that of the soil, resulting in water uptake by the shallow roots and flow up the plant stems toward the canopy. At Bednesti, as mean daily θ_v fell during the 12-day period shown in Figure 14, soil water potential (ψ_s) decreased from -0.15 MPa on 1 July to a minimum of -6.0 MPa on 11 July. It is important to note that the resolution and accuracy

of the gypsum blocks decreases as soil water potential falls below the range of -1.0 to -1.5 MPa. For this reason, we should not overly focus on absolute values for soil water potential during the period of 10–12 July. Rather, we should concentrate on the trend of decreasing amplitude in the diurnal drawdown of θ_v as soil water potential fell below -1.0 MPa, which suggests that ET is becoming increasingly limited by soil moisture availability. It is conventionally accepted that ψ_s values in the range of -1.0 to -1.5 MPa mark the lower limit of water that is available for uptake (e.g., Black and Mitchell 1990). Our data suggest that ET does not completely stop when ψ_s reaches -1.5 MPa at a depth of 15 cm (where the gypsum blocks were located) but continues at a substantially lower rate than when there are no available water limitations at that depth. We speculate that ongoing low rates of ET may be possible because of water that is being hydraulically redistributed to surface soils via roots at greater depth that have access to moister soil layers.

The relationship between θ_v and ψ_s for the 2012–2015 growing seasons is shown in Figure 15. The data show that ψ_s declines sharply when θ_v drops below 0.14 m^3/m^3, which is consistent with soil water retention curves presented in the literature for sandy-loam to loamy-sand textured soils (e.g., Kramer 1983) such as those at Bednesti. When a sharp decline in ψ_s occurs, most of the available water in soil pores has been used and replaced by air. Much of the remaining water is tightly held by soil particles and is unavailable for plant use. The relationship between ψ_s and θ_v at the Bednesti site suggests that soil water availability may be limiting lodgepole pine ET when θ_v drops below 0.14 m^3/m^3, which it generally did during the period of late July to early August. It was common for θ_v to remain low during August and September until significant fall precipitation events began. By that time, other factors such as reductions in air temperature and solar radiation (e.g., Kozlowski and Pallardy 1997) would have been limiting stomatal opening and thus ET.

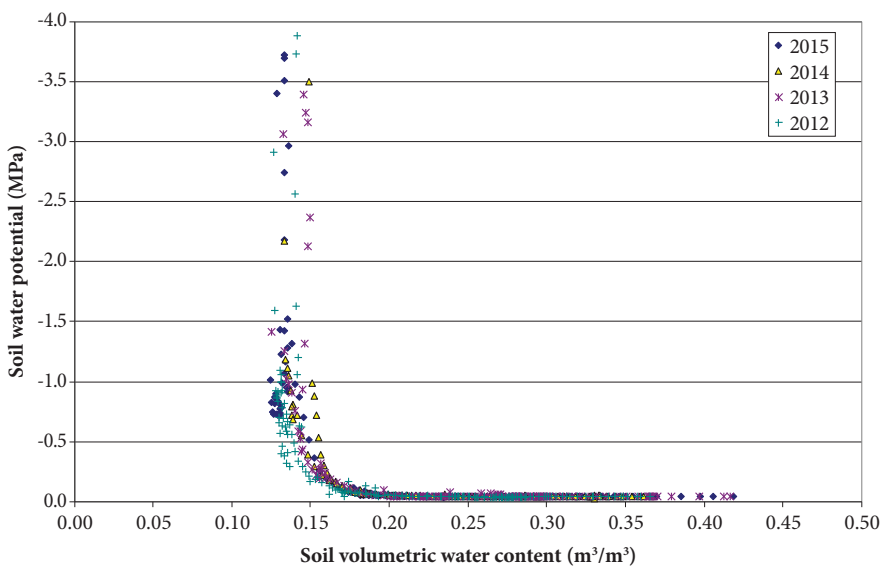

FIGURE 15 *Soil water retention curve showing the relationship between soil volumetric water content (θ_v) and soil water potential (ψ_s) in the reforested area for the years 2012, 2013, 2014, and 2015. Soil water potential data for 2016 and 2017 are not included due to aging (and therefore less reliable) sensors.*

3.3 Correlations between Climate or Microclimate and Lodgepole Pine Growth

3.3.1 Climate and lodgepole pine seasonal growth trends 1992–1994

In combination with the ongoing collection of air temperature and precipitation data at Bednesti, lodgepole pine height and diameter growth data were collected at approximately 2-week intervals during the growing seasons of 1992, 1993, and 1994, and these provide an opportunity to examine relationships between seasonal growth and climate variables. The seasonal conifer growth data have not previously been published, and it is beyond the scope of this report to present the results in full; here we present results for plot C1 only.

At Bednesti, budbreak occurred in the last 2 weeks of May in 1992 and 1993, and in the first 2 weeks of May in 1994 (Figure 16). It is generally accepted that the timing of conifer budbreak is related to chilling and heat

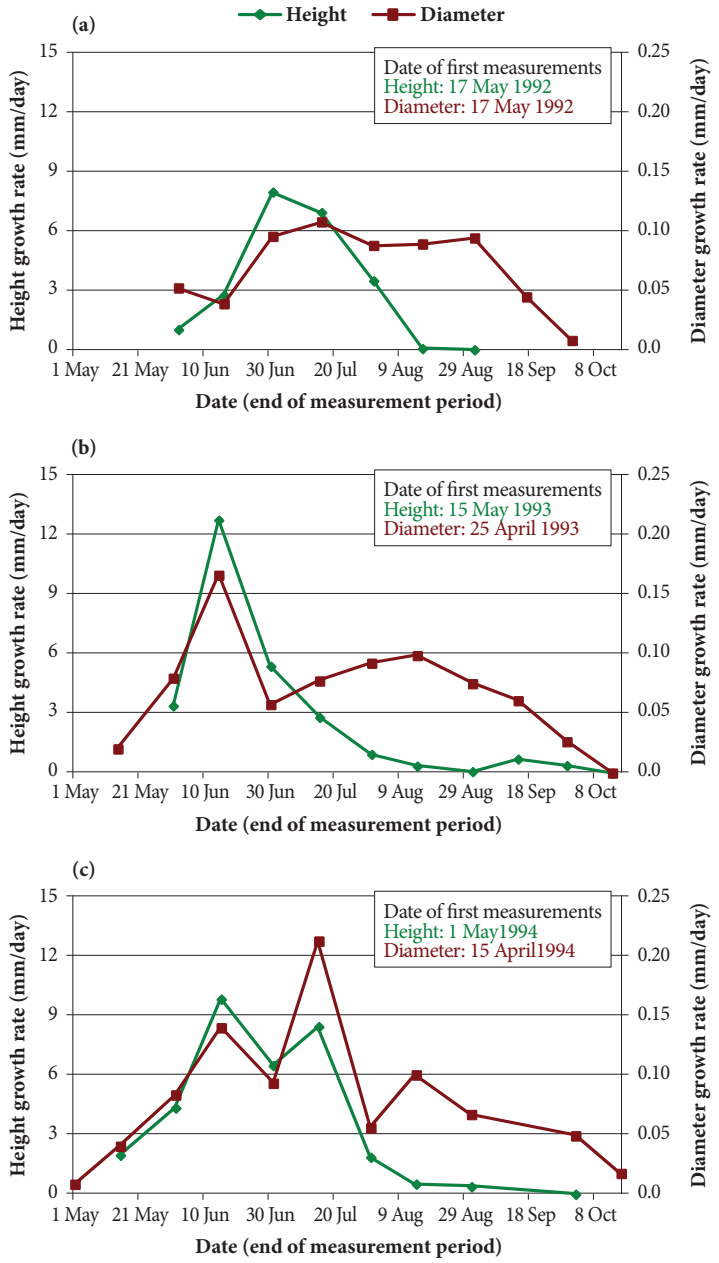

FIGURE 16 *Seasonal trends in lodgepole pine height and diameter growth rates in the disc trench hinge treatment (plot C1) from May to October in (a) 1992, (b) 1993, and (c) 1994.*

sum requirements (e.g., Hannerz 1999). In general, the growth strategy of trees in boreal and sub-boreal regions involves balancing the length of the growing season against the risk of damage from late or early frost events (Green 2007). Early budburst can be advantageous where growing-season moisture is limiting because it allows height growth to be completed before moisture is depleted by summer drought (Gould et al. 2011). Such an adaptation could become increasingly important in the SBSdw3 if summer drought intensifies due to the warmer temperatures predicted for the central interior of British Columbia (Pacific Climate Impacts Consortium 2013). At Bednesti, we estimated that 95% of annual height growth (i.e., 95% of leader extension) was completed by 27 July in 1992, by 1 August in 1993, and by 24 July in 1994. An examination of soil moisture data collected at Bednesti from 2012 to 2015 indicates that late July to early August is also the period when soil moisture availability falls to levels that are potentially limiting to conifer seedlings (see Section 3.2.2).

Diameter growth in plot C1 commenced in the last week of April in 1993 and 1994 and was under way by 17 May in 1992 (1992 was the first year seasonal growth measurements were attempted and the initial measurement did not capture the onset of diameter growth). Peaks in the rates of height and diameter growth were concurrent (Figure 16), but diameter growth exhibited additional peaks in 1993 and 1994. In both those years, a late summer (August) peak in diameter growth occurred after the cessation of height growth. Ninety-five percent of annual diameter growth (i.e., 95% of the annual increment in diameter) is estimated to have been completed by 9 September in 1992, by 12 September in 1993, and by 23 September in 1994. Minor amounts of diameter growth continued until at least the end of September in all 3 years. We speculate that the early peaks in diameter growth that were coincident with height growth peaks may have been associated with the development of earlywood, while later peaks may have been associated with latewood production (Jozsa and Middleton 1994).

Factors affecting seasonal diameter growth of conifer seedlings are not well documented, but there is a general assumption (e.g., Coates et al. 1994) that diameter growth responds to seasonal climate. This is true of mature trees for which environmental factors, such as air temperature, photoperiod, and soil temperature, influence the timing of xylem cell differentiation (Rossi et al. 2014). For Douglas-fir (*Pseudotsuga menziesii*) in Oregon, Beedlow et al. (2013) noted that basal area accumulation was influenced by an interaction between air temperature and soil water availability, especially on drier sites. At Bednesti, visual examination of plot C1 data suggested that growing degree-day peaks appeared to precede peaks in diameter growth rate by 2 weeks (Figure 17). There were no visually evident relationships between precipitation during the 2-week intervals for either height or diameter growth. Structural time-series analysis of these data was attempted but was inconclusive because of the small sample sizes. Further examination of the full set of seasonal growth data collected at Bednesti is warranted. The effect that soil moisture availability may have on the seasonal growth of young seedlings is especially important given that growing-season climatic conditions in the general region are predicted to become warmer and possibly also drier (Pacific Climate Impacts Consortium 2013).

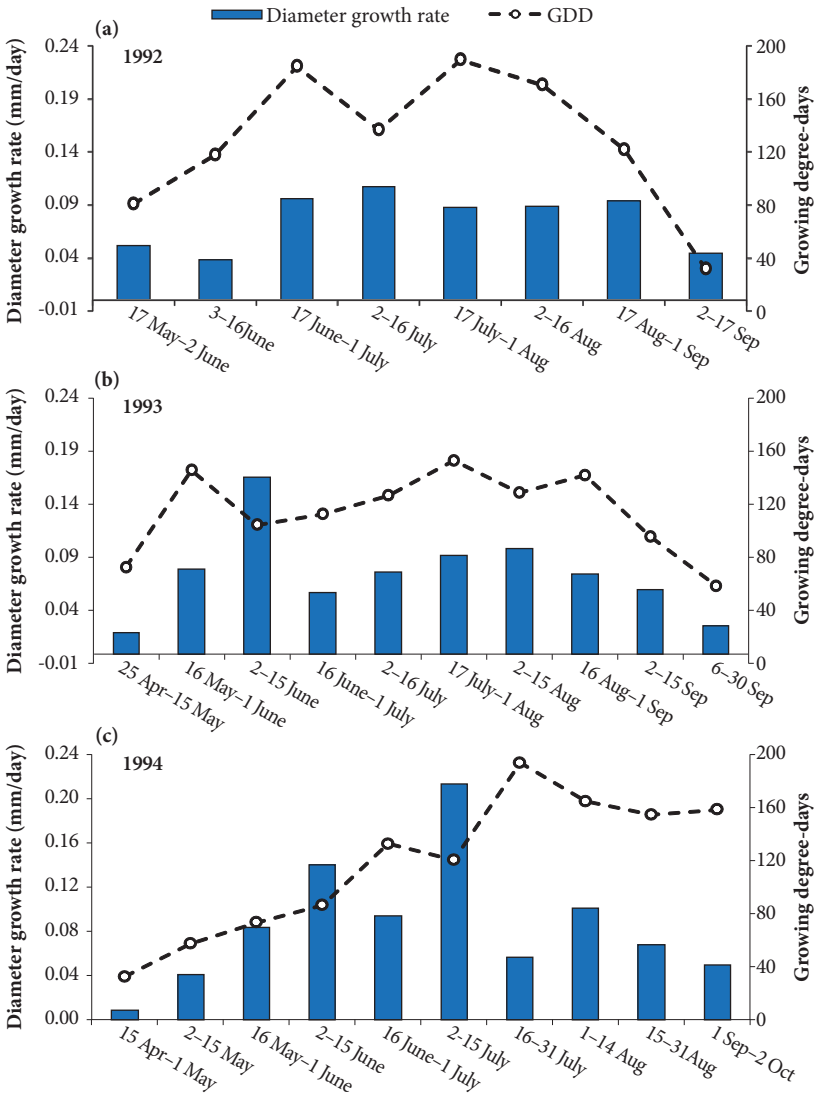

FIGURE 17 *Trends in seasonal diameter growth and growing degree-days from April to October in disc trench treatment plot C1 in (a) 1992, (b) 1993, and (c) 1994.*

3.3.2 Microclimate and lodgepole pine height growth 1999–2017

Although the literature generally suggests that, for lodgepole pine, weather conditions in the year previous to leader extension (when buds are formed) are a more important determinant of potential annual height than current-year conditions (Dougherty et al. 1994; Chuine et al. 2001), data from plot C1 at the Bednesti site suggest a possible relationship between growing-season soil moisture availability and annual height growth. We visually compared trends in annual height growth with trends in June–September mean θ_v, and the total number of days when May–September θ_v was less than 0.14 m^3/m^3 (Figure 18). Both seasonal mean θ_v and the number of days when θ_v was less than 0.14 m^3/m^3 appeared to be correlated with the total annual height growth of lodgepole pine. Years with short periods of drought stress and high average θ_v appeared to have greater height growth, while years with longer periods of drought stress tended to have less height growth. Assuming that the daily drawdown of θ_v seen in Figure 14 is primarily related to ET by the pine canopy, we thought that quantifying this drawdown could provide

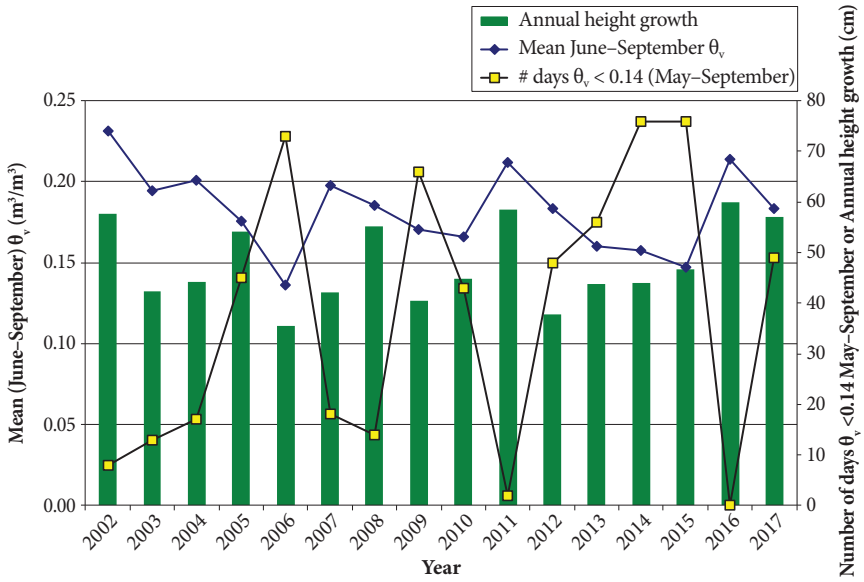

FIGURE 18 *Mean annual lodgepole pine height growth in plot C1, mean (June–September) soil volumetric water content (θ_v), and the number of days during the growing seasons when θ_v was below 0.14 m^3/m^3.*

insight into the extent to which soil water availability affects annual height growth. To test this hypothesis, we proposed an ET index and did some sample calculations in Appendix 4. This index is presented in an appendix rather than as part of the Results section in acknowledgement that one measurement of θ_v is not adequate to represent soil moisture throughout the entire rooting zone, and nor is it adequate to represent soil moisture spatially throughout the plot. Nonetheless, the relationship we observed is interesting and may warrant further investigation.

3.4 Microclimate and Lodgepole Pine Responses beneath Dense Aspen (Plot A2)

Aspen is common throughout central British Columbia and, at overtopping densities higher than 1000 stems/ha, it is a potentially strong competitor with lodgepole pine in the SBSdw (Newsome et al. 2012; Newsome and Heineman 2016). Reductions in light availability are especially problematic for lodegpole pine because it is among the least shade tolerant of conifer species (Kobe and Coates 1997; Coates and Burton 1999; Klinka et al. 2000). At Bednesti, the localized dense stand of aspen that developed in plot A2 in response to 1987 soil disturbance had a density of approximately 19 000 stems/ha and an average canopy height of 6.7 m in 1997. By 2015, the aspen canopy height was approximately 12 m.

3.4.1 Light We selected 2014 as a representative year for describing light conditions beneath the aspen canopy. During the growing season, when the aspen had achieved full leaf area, daily average PAR below the canopy in plot A2 was in the range of 30–80 $\mu mol \cdot m^{-2} \cdot s^{-1}$ compared with 250–600 $\mu mol \cdot m^{-2} \cdot s^{-1}$ in the open area (Figure 19a). Figure 19b shows the ratio of PAR measured at 1 m above the ground in plot A2 with that measured at a height of 3 m in the open area next to plot C1. From late May through late August, the total transmissivity of PAR through the combined canopy of aspen and pine in plot A2 was between 10 and 20% of the radiation incident at the top of the canopy. The sensor in plot A2 was located in what was deemed a representative location; however, we recognize that one measurement of PAR does not constitute a spatial average of light availability within the aspen stand.

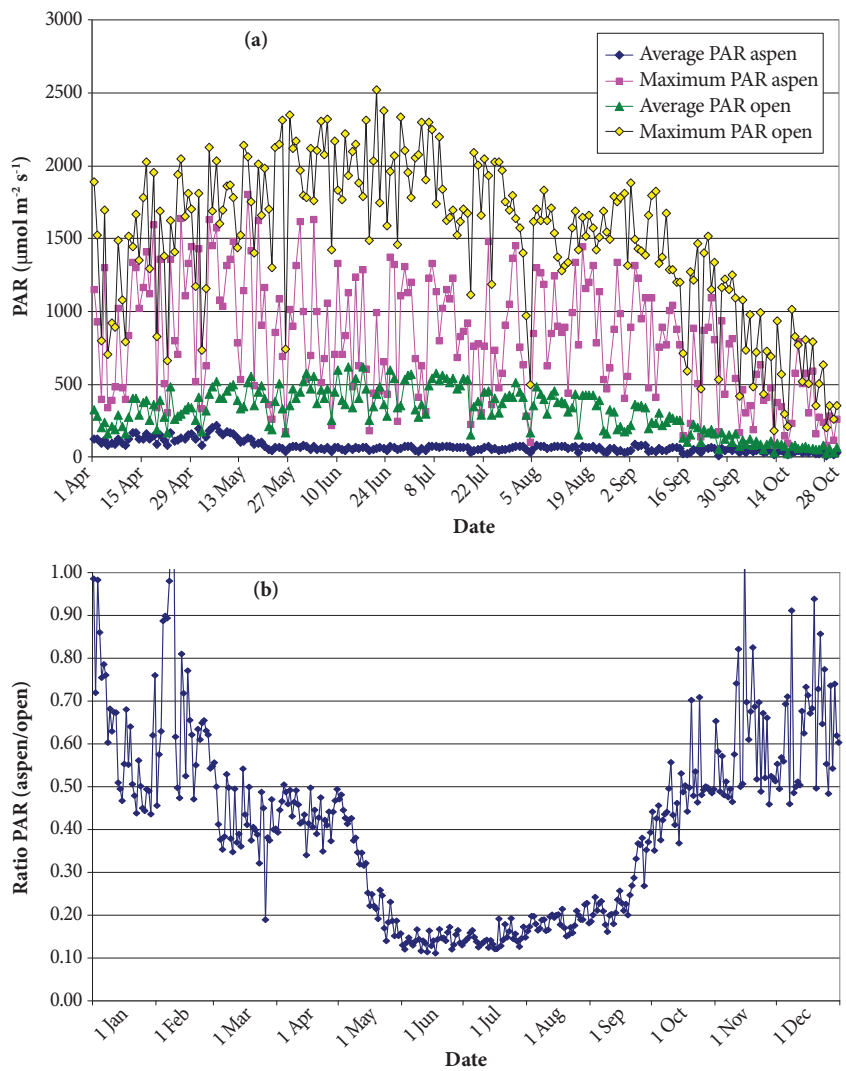

FIGURE 19 *Comparison of PAR beneath the aspen canopy and in open conditions in 2014: (a) daily average and maximum PAR in plot A2 beneath the aspen canopy versus PAR measured at a height of 3 m in the opening beside plot C1, and (b) the ratio of PAR measured beneath the aspen canopy (plot A2) to that measured in the open (plot C1).*

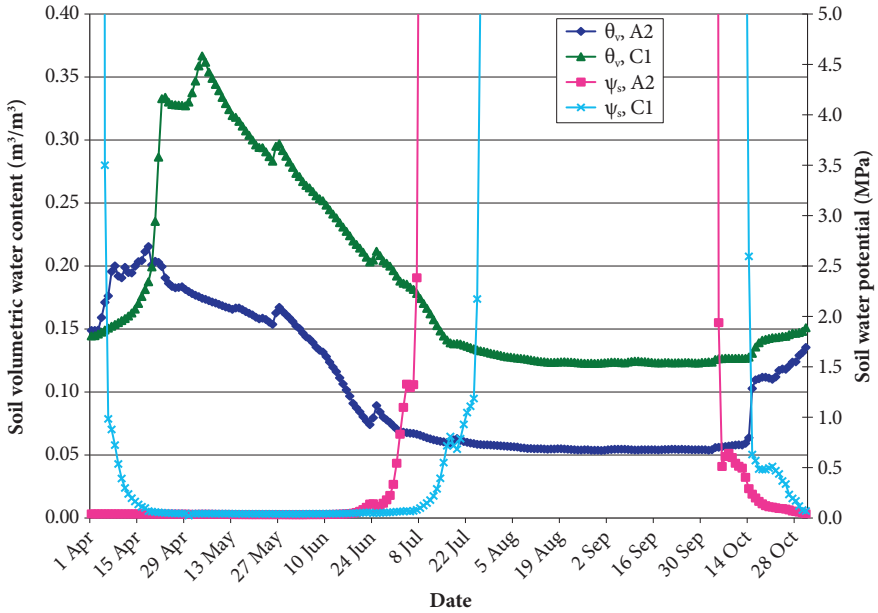

FIGURE 20 *Comparison of soil volumetric water content (θ_v) and soil water potential (ψ_s) in plot A2 (under the aspen canopy) and plot C1 (reforested) for the 2014 growing season.*

3.4.2 Soil moisture Figure 20 illustrates the differences in daily θ_v and ψ_s between plots A2 and C1 during the 2014 growing season. The lower end of available water, as indicated by rapidly declining soil water potentials, occurs near water contents of 0.14 m^3/m^3 in plot C1 and near 0.07 m^3/m^3 in plot A2. This rapid decline in soil water potential at Bednesti commonly occurs during July and August as available water is used up and is associated with declining ET rates as described in Figure A4-1 of Appendix 4. In 2014, soil water potentials in plot A2 dropped to levels that would cause stress in lodgepole pine about 2 weeks earlier than those in plot C1, and a similar trend was observed during other growing seasons. Early-season water use by aspen during the period when leaves come out is a possible explanation for the drier conditions in plot A2 than plot C1. A recent study in Alaska suggests that, in early spring, deciduous trees are capable of taking up 21–25% of snowmelt water during the same period that conifers take up < 1% (Young-Robertson et al. 2016). The fact that water holding capacity declines as soil texture gets coarser (Hillel 1980) may also have contributed to drier growing-season conditions in plot A2; soils had a consistent loamy sand texture in plot A2 compared with sandy loam to loamy sand in plot C1.

3.4.3 Lodgepole pine responses In year 25 (2012), lodgepole pine survival was 73% in plot A2 compared with 92% in plot C1. Mortality cause was not initially recorded in the Bednesti study, and while we assume that light competition by aspen played a role in early mortality in plot A2, other factors likely also contributed. Fifteen percent of the pine in plot A2 died by age 4, which is earlier than we would expect if light competition was the only issue. In particular, hare damage may have been a contributing factor; anecdotal comments indicate that clipping damage to pine was high in plot A2, probably because aspen provided the animals with cover.

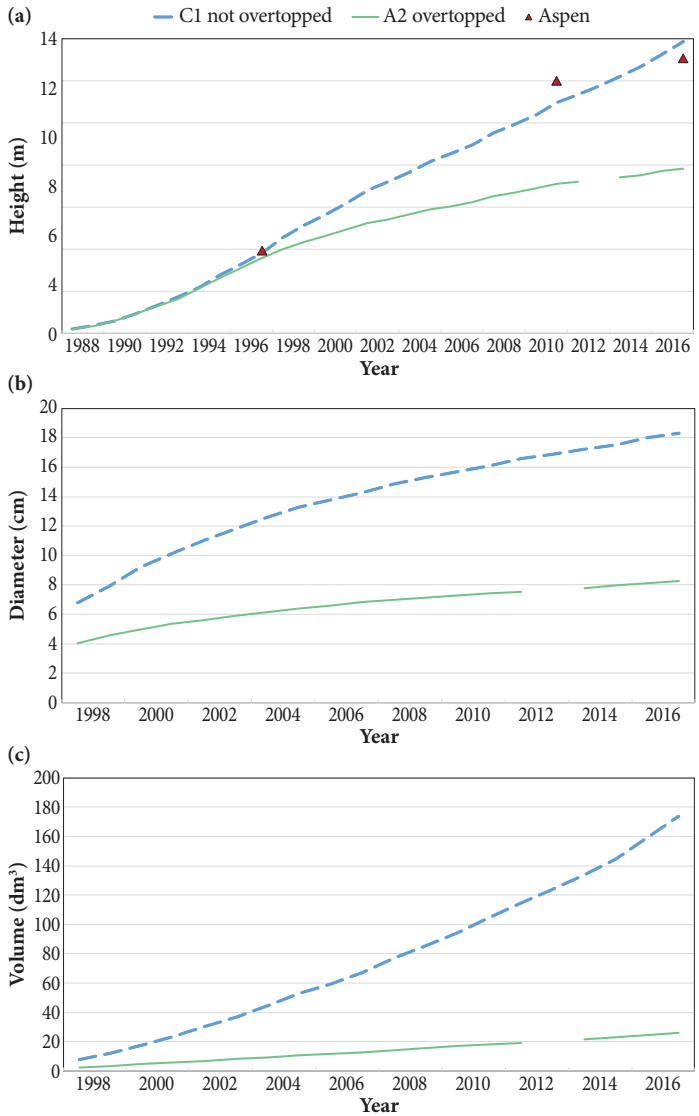

FIGURE 21 *Comparisons of overtopped (plot A2, overtopped trees only) and not-overtopped (plot C1) lodgepole pine size from 1988 to 2017 (age 1–30 years): (a) annual mean pine height from 1988 to 2017 and aspen height in 1997, 2011, and 2017, (b) mean pine diameter at breast height (1.3 m) from 1988 to 2017, and (c) mean pine stem volume (calculated using a taper equation) from 1988 to 2017.*

Of the 35 pine that survived to 2012 in plot A2, 26 were judged to be overtopped. The growth of these 26 trees was compared with that of non-overtopped pine in plot C1. For the first decade after planting, the height growth of non-overtopped pine on plot C1 and overtopped pine on plot A2 was comparable; however, from age 11 (1998) through age 30 (2017), there was a steady decline in height growth of pine in plot A2 relative to those in plot C1 (Figure 21a). By age 30, overtopped pine in plot A2 averaged 6.0 m shorter than the non-overtopped pine in plot C1. Reduced height growth is a sign of severe competitive stress in shade-intolerant lodgepole pine; in a more southerly SBSdw variant, Newsome et al. (2003) reported that where naturally regenerated pine was overtopped by ≥ 5000 aspen/ha, the trees exhibited significant reductions in height, and low vigour, compared with open-grown trees. At Bednesti, overtopped pine

also increased in diameter and stem volume more slowly than those that were not overtopped; at age 28, pine in plot A2 had slightly less than one-half the stem diameter and approximately 14% of the stem volume of the pine in plot C1 (Figures 21b, c).

The light saturation point for lodgepole pine growing in shaded areas is between 600 and 700 $\mu mol \cdot m^{-2} \cdot s^{-1}$ and the light compensation point is between 20 and 30 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (Carter and Smith 1988; Landhausser and Lieffers 2001). In plot A2 at Bednesti, the growing-season daily average PAR at a height of 1 m was much closer to the light compensation point than the saturation point. Although maximum daily PAR values were typically above the light saturation point, these were likely the result of sun flecks that occurred for brief periods. Although PAR beneath the aspen canopy was not assessed prior to 2012 (stand age 25 years), the high density of aspen and the extent to which it overtopped the pine suggests that light levels in plot A2 were likely suboptimal for pine growth during much of the preceding period of 1988–2011. Comeau et al. (2006) demonstrated that the light available to conifers growing within aspen canopies increases steeply when the conifers achieve at least 70% of the aspen height; however, in plot A2, even the tallest overtopped lodgepole pine had not achieved that benchmark by age 28 (mean ± standard deviation of 726 cm ± 202 cm).

Moisture stress associated with the overall drier soil conditions of plot A2 and the 1- to 2-week longer period where soil water availability was limiting to ET (Figure 20) may also have contributed to poor pine growth in that plot. Lodgepole pine is drought tolerant (Klinka et al. 2000); however, its growth strategy of allocating resources to height growth at the expense of root growth in light-limited environments, thus reducing its ability for water uptake (Landhäusser and Lieffers 2001), may have further exacerbated moisture stress. In addition to height growth reductions, another indication of the poor condition of overtopped pine in plot A2 is their slow diameter growth. Kobe and Coates (1997) related minimum annual radial growth rates of various tree species to the probability of mortality within 3 years; according to their models, mean annual radial growth rates of 2–2.5 mm/year are required for predicted mortality rates to be negligible. In plot A2, from 2015 to 2017, the mean radial growth rate for overtopped pine was 0.8 mm/year, which according to the Kobe and Coates model leads to an estimated 3-year probability of mortality of up to 40%. In contrast, pine that were not overtopped in plot C1 grew radially at an average 1.9 mm/year during the same period.

4 CONCLUSIONS

Data collected at the Bednesti research site and nearby ECCC weather stations provide some evidence of climate change occurring in that geographic area. Mean annual air temperature appears to have increased during the last decade, while extreme winter minimum air temperatures are no longer commonly reaching -40°C. Mean growing-season air temperatures for the period 2013–2015 represent the warmest 3-year interval since the year 2000 at the Bednesti site. The climate is possibly also becoming drier; growing-season precipitation at the Bednesti research site was below the 30-year normal for seven of the last nine growing seasons. These measured data are consistent with predicted future climate scenarios for the geographic area that includes Bednesti; all scenarios predict warmer growing-season air temperatures, and some predict less precipitation (Pacific Climate Impacts Consortium 2013). Even with unchanged or somewhat higher precipitation, significantly warmer air temperatures will likely lead to drier soil conditions and increased water stress for lodgepole pine.

We note that the timing of the end of the height growth season appeared to coincide with declines in soil water content that typically occurred in late July or early August at Bednesti. Although we lack sufficient soil moisture data to properly investigate this relationship, we believe it warrants further investigation. If future climatic trends for the Nechako region west of Prince George result in soils becoming critically dry earlier in the summer, the overall productivity of lodgepole pine in that region may decrease. Since crown closure probably contributes to soil moisture deficits by reducing the amount of precipitation that reaches the forest floor, this raises questions about density management of lodgepole pine stands, both at the time of planting and with regard to the timing of potential thinning operations. Increases in the recommended planting density for lodgepole pine are currently being considered for interior British Columbia with the objectives of improving tree form, wood quality, and timber supply through the earlier creation of closed canopy conditions that stimulate crown lift. Further work should be done to investigate possible negative effects on height growth (and, by conjecture, volume accumulation) related to soil moisture deficits, as these may become more severe with climate change. Further investigation could also suggest where thinning operations will be most effective; they may provide the greatest benefit on sites where moisture is most limiting.

Our preliminary investigation of the influence that GDD accumulation and precipitation may have had on seasonal growth of lodgepole pine during the 1992–1994 growing seasons was inconclusive, largely because of the small sample size (we used data from plot C1 only). The full data set warrants further investigation, particularly regarding the timing of diameter growth. Our data indicate that peaks in diameter growth occur at approximately the same time as peaks in height growth during the early part of the growing season, and presumably correspond with earlywood production. Trends in late-season diameter growth and the presumed production of higher-density latewood are of particular interest because of the importance that wood density has on wood quality (Jozsa and Middleton 1994).

As anticipated, lodgepole pine growing among the extremely dense aspen in plot A2 are doing poorly at age 30. Our data suggest that, in addition to low light levels, soil moisture deficits that were possibly related to early-season water use by aspen and localized differences in soil texture and water holding capacity, may have contributed to the decline of the overtopped pine. The climate station that was installed in plot A2 in 2012 (at a stand age of 25 years) will allow us to track changes in below-canopy light and soil moisture conditions within dense aspen as the stand ages. These data may eventually be useful for improving the ability of growth and yield modelling tools, such as TASS, to simulate conditions in mixedwood and overtopped stands in the SBSdw.

Climate and microclimate data are often collected in silviculture studies as a means of interpreting tree growth responses. These data are expensive and time consuming to collect and are often considered to be of secondary importance in management of the overall project. In many cases, climate data are not examined with the same level of intensity as the tree data and are not presented as stand-alone results. The exercise of reporting as fully as possible on the Bednesti climate data has provided us with a number of insights. First, unexpected relationships between tree growth and environmental factors may come to light when the primary focus is examination of the climate or microclimate data. For example, we would not have identified a possible correlation between soil moisture availability and annual height growth if we had not been investigating microclimate data in detail. The project also demonstrated the importance of consistency in maintaining metadata relating to climate and microclimate data collection. In the case of the Bednesti study, it is remarkable that climate data collection continued, in some form, throughout the 30-year span of the project. However, metadata were maintained somewhat inconsistently in the early years of the project, which rendered some parts of the data set unusable for the present report. We emphasize that, where these valuable data have been collected, as much effort should go into their maintenance as is expended on the tree data. Finally, data collected over several decades often proves to be highly valuable for reasons other than those identified in the original objectives for a project. Climate change was not recognized as highly important to forest management in the mid-1980s when the Bednesti experiment was initiated; however, the long-term collection of climate data at that site has provided specific information about how weather patterns have changed during the past one-quarter century in the geographic region west of Prince George, and how these changes may be affecting mid-rotation lodgepole pine growth.

5 LITERATURE CITED

Beedlow, P.A., E.H. Lee, D.T. Tingey, R.S. Waschmann, and C.A. Burdick. 2013. The importance of seasonal temperature and moisture patterns on growth of Douglas-fir in western Oregon, USA. Agricultural and Forest Meteorology 169:174–185.

Boateng, J.O., J.L. Heineman, L., Bedford, G.J. Harper, and A.F.L. Nemec. 2009. Long-term effects of site preparation and post-planting vegetation control on *Picea glauca* survival, growth and predicted yield in boreal British Columbia. Scand. J. For. Res. 24:111–129.

Boateng, J.O., J.L. Heineman, L., Bedford, and A.F.L. Nemec. 2010. Twenty-year effects of mechanical site preparation and windrow burning treatments on soil properties and *Pinus contorta* var. *latifolia* nutrition in sub-boreal British Columbia. Scand. J. For. Res. 25(6):515–533.

Boateng, J.O., J.L. Heineman, L. Bedford, A.F.L. Nemec, J. McClarnon, and R.A. Powelson. 2012. Twenty-year site preparation effects on sub-boreal lodgepole pine performance. New Forests 43:457–472.

Black, A. and B. Mitchell. 1990. Effects of site preparation treatments on soil moisture regime in IDFdk, MSxk and ESSFxc clearcuts – project 3.02. FRDA Research Memo 162.

Carter, G.A. and W.K. Smith. 1988. Microhabitat comparisons of transpiration and photosynthesis in three subalpine conifers. Can. J. Bot. 66:963–969.

Chuine, I., S.N. Aitken, and C.C. Ying. 2001. Temperature thresholds of shoot elongation in provenances of *Pinus contorta*. Can. J. For. Res. 31:1444–1455.

Claveau, Y., C. Messier, P.G. Comeau, and K.D. Coates. 2002. Growth and crown morphological responses of boreal conifer seedlings and saplings with contrasting shade tolerance to a gradient of light and height. Can. J. For. Res. 32:458–468.

Coates, K.D. and P.J. Burton. 1999. Growth of planted tree seedlings in response to ambient light levels in northwestern interior cedar-hemlock forests of British Columbia. Can. J For. Res. 29(9):1374–1382.

Coates, K.D., S. Haeussler, S. Lindeburgh, R. Pojar, and A.J. Stock. 1994. Ecology and silviculture of interior spruce in British Columbia. B.C. Min. For. and Can. For. Serv. FRDA Rep. 220.

Comeau, P.G., J.L. Heineman, and T. Newsome. 2006. Evaluation of relationships between understorey light and aspen basal area in the British Columbia central interior. For. Ecol. Manag. 226:80–87.

Dawson, A.B. 1989. Soils of the Prince George - McLeod Lake area (MOE Technical Report 029). Victoria, B.C. Ministry of Agriculture and Fisheries.

Delong, C., D. Tanner, and M.J. Jull. 1993. A field guide for site identification and interpretation for the southwest portion of the Prince George Forest Region. B.C. Min. For., Victoria, BC, Land Manag. Handb. 24. www.for.gov.bc.ca/hfd/pubs/Docs/Lmh/Lmh51.htm.

Delucia, E.H. 1986. Effect of low root temperature on net photosynthesis, stomatal conductance, and carbohydrate concentration in Engelmann spruce (*Picea engelmannii* Parry ex Engelm.) seedlings. Tree Physiol. 2:143–154.

Delucia, E.H. and W.K. Smith. 1987. Air and soil temperature limitations on photosynthesis in Engelmann spruce during summer. Can. J. For. Res. 17:527–533.

Dougherty, P.M., D. Whitehead, and J.M. Vose. 1994. Environmental influences on the phenology of pine. Ecological Bulletins 43:64–75.

Egginton, V.N. 2005. Historical climate variability from the instrumental record in northern British Columbia and its influence on slope stability. M.Sc. thesis. Simon Fraser University, Vancouver, B.C.

Fleming, R.L., T.A. Black, R.S. Adams, and R.J. Stathers. 1998. Silvicultural treatments, microclimatic conditions and seedling response in Southern Interior clearcuts. Can. J. Soil Science 78:115–126.

Fleming, R.L., T.A. Black, and N.R. Eldridge. 1994. Effects of root zone soil water regimes in high-elevation forest clearcuts. For. Ecol. Manag. 68:173–188.

Gould, P.J., C.A. Harrington, and J.B. St. Clair. 2011. Incorporating genetic variation into a model of budburst phenology of coast Douglas-fir (*Pseudotsuga menziesii* var. *menziesii*). Can. J. For. Res. 41:139–150.

Green, D.S. 2007. Controls of growth phenology vary in seedlings of three, co-occurring ecologically distinct northern conifers. Tree Physiol. 27:1197–1205.

Grossnickle, S.C. 2005. Importance of root growth in overcoming planting stress. New Forests 30:273–294.

Haeussler, S., D. Coates, and J. Mather. 1990. Autecology of common plants in British Columbia: a literature review. For. Can. and B.C. Min. For., Victoria, B.C. FRDA. Rep. 158.

Hannerz, M. 1999. Evaluation of temperature models for predicting bud burst in Norway spruce. Can. J. For. Res. 29:9–19.

Hillel, D. 1980. Fundamentals of soil physics. Academic Press, Orlando, Fla.

Jozsa, L.A. and G.R. Middleton. 1994. A discussion of wood quality attributes and their practical implications. Forintek Canada Corp. Special Publication No. SP-34. https://www.for.gov.bc.ca/hfp/publications/00032/SP-34%20(2).pdf (Accessed Jan. 24, 2017).

Klinka, K., J. Worrall, L. Skoda, and P. Varga. 2000. The distribution and synopsis of ecological and silvical characteristics of tree species of British Columbia's forests. Canadian Cartographics Ltd., Coquitlam, B.C.

Kobe, R.K. and K.D. Coates. 1997. Models of sapling mortality as a function of growth to characterize interspecific variation in shade tolerance of eight tree species of northwest British Columbia. Can. J. For. Res. 27:227–236.

Kozlowski, T.T. and S.G. Pallardy. 1997. Physiology of woody plants. Academic Press, San Diego, Calif.

Kramer, P.J. 1983. Water relations of plants. Academic Press Inc., Orlando, Fla.

Lajzerowicz, C.C., M.B. Walters, M. Krasowski, and H.B. Massicotte. 2004. Light and temperature differentially colimit subalpine fir and Engelmann spruce seedling growth in partial-cut subalpine forests. Can. J. For. Res. 34(1):249–260.

Landhäusser, S.M. and V.J. Lieffers. 2001. Photosynthesis and carbon allocations of six boreal tree species grown in understorey and open conditions. Tree Physiol. 21:243–250.

LePage, P. and K.D. Coates. 1994. Growth of planted lodgepole pine and hybrid spruce following chemical and manual vegetation control on a frost-prone site. Can. J. For. Res. 24:208–216.

Lundmark, T. and J.E. Hällgren. 1987. Effects of frost on shaded and exposed spruce and pine seedlings planted in the field. Can. J. For. Res. 17:1197–1201. www.nrcresearchpress.com/doi/pdf/10.1139/x87-184 (Accessed Dec. 2017).

McClarnon, J., J.L. Heineman, R.A. Powelson, J.O. Boateng, L. Bedford, A.F.L. Nemec, and T. Kaffanke. 2016. Lodgepole pine responses to mechanical site preparation and burning in sub-boreal British Columbia: 19–25 year results from three SBS zone studies (EP995). Prov. B.C., Victoria, B.C. Tech. Rep. 094. https://www.for.gov.bc.ca/hfd/pubs/Docs/Tr/TR094.htm

Newsome, T. and J.L. Heineman. 2016. Adjusting free-growing guidance regarding aspen retention in the Cariboo-Chilcotin. Prov. B.C., Victoria, B.C. Tech. Rep. 102. https://www.for.gov.bc.ca/hfd/pubs/Docs/Tr/TR102.htm

Newsome, T., J.L. Heineman, and A. Nemec. 2003. Competitive effects of trembling aspen on lodgepole pine performance in the SBS and IDF zones of the Cariboo-Chilcotin region of south central British Columbia. Res. Br., B.C. Min For., Victoria, B.C. Tech Rep 005. https://www.for.gov.bc.ca/hfd/pubs/Docs/Tr/Tr005.htm

_____. 2012. Identifying and characterizing important trembling aspen competitors with juvenile lodgepole pine in three south-central British Columbia ecosystems. Int. J. For. Res. Vol. 2012, Article ID 573640.

_____. 2016a. Long-term results from EP841: Douglas-fir, lodgepole pine, and hybrid spruce responses to mechanical site preparation in the Interior Douglas-fir and Sub–Boreal Spruce Zones of south-central British Columbia. Prov. B.C., Victoria, B.C. Tech. Rep. 092. www.for.gov.bc.ca/hfd/pubs/Docs/Tr/Tr092.htm.

_____. 2016b. Plantation establishment strategies for hybrid spruce and lodgepole pine on high-elevation sites in wet Cariboo ESSF subzones: 17-year results (EP1021). Prov. B.C., Victoria, B.C. Tech. Rep. 093. www.for.gov.bc.ca/hfd/pubs/Docs/Tr/Tr093.htm.

Pacific Climate Impacts Consortium. 2013. Climate summary for Omineca Region. PCIC, Univ. Victoria. https://www.pacificclimate.org/sites/default/files/publications/Climate_Summary-Omineca.pdf.

Prieto, I., C. Armas, and F.I. Pugnaire. 2011. Water release through plant roots: new insights into its consequences at the plant and ecosystem level. New Phytologist 193:830–841.

Reich, R.W., J.L. Heineman, A.F.L. Nemec, L. Bedford, J.O. Boateng, and T. Kaffanke. 2015. Hard pine stem rusts on lodgepole pine at a site preparation study in sub-boreal British Columbia: effects over 24 years. Can. J. For. Res. 45:411–421.

Rossi, S., A. Deslauriers, C. Lupi, and H. Morin. 2014. Control over growth in cold climates. In: Trees in a changing environment. Springer, Dordrecht, Netherlands, pp. 191–219.

Running, S.W. and C.P. Reid. 1980. Soil temperature influences on root resistance of *Pinus contorta* seedlings. Plant Physiol. 65:634–640.

Safranyik, L. and A.L. Carroll. 2006. The biology and epidemiology of the mountain pine beetle in lodgepole pine forests. In: The mountain pine beetle: a synthesis of biology, management, and impacts on lodgepole pine. L. Safranyik and B. Wilson (editors). Natural Resources Canada, Canadian Forest Service, Victoria, B.C., pp. 3–66.

Sagar, R.M. and M.J. Waterhouse. 2015. Microclimate studies in mountain pine beetle – damaged silvicultural systems on the Chilcotin Plateau: the Itcha-Ilgachuz project (1997-2013). Prov. B.C., Victoria, B.C. Tech Rep. 089. www.for.gov.bc.ca/hfd/pubs/Docs/Tr/Tr089.htm (Accessed Dec. 2017).

Sagar, R.M., M.J. Waterhouse, and B. Chapman. 2005. Microclimate studies in silvicultural systems on the Chilcotin Plateau of British Columbia: the Itcha-Ilgachuz project (1997–2003). B.C. Min. For., Res. Br., Victoria, B.C. Tech. Rep. 022. www.for.gov.bc.ca/hfd/pubs/Docs/Tr/Tr022.htm (Accessed Dec. 2017).

Soil Classification Working Group. 1998. The Canadian system of soil classification (Publ. 1646). Ottawa, Ont. Agric. and Agri-Food Canada.

Spittlehouse, D. 2006. Annual water balance of high elevation forests and clearcuts. In: Proc. 27th Conf. Agricultural and Forest Meteorology, Am. Meteorol. Soc., San Diego, Calif. http://ams.confex.com/ams/pdfpapers/110083.pdf (Accessed Feb. 2016).

Spittlehouse, D.L. and R.J. Stathers. 1990. Seedling microclimate. B.C. Min. For., Victoria, B.C. Land Manag. Rep. 65.

Steen, O.A., R.J. Stathers, and R.A. Coupé. 1990. Identification and management of summer frost-prone sites in the Cariboo Forest Region. For. Can. and B.C. Min. For., Victoria, B.C. FRDA Report 157. www.for.gov.bc.ca/hfd/pubs/Docs/Frr/Frr157.htm (Accessed Mar. 2016).

Wolken, J.M., S.M. Landhäusser, V.J. Lieffers, and U. Silins. 2011. Seedling growth and water use of boreal conifers across different temperatures and near-flooded soil conditions. Can. J. For. Res. 41:2292–2300.

Wright, E.F., K.D. Coates, C.D. Canham, and P. Bartemucci. 1998. Species variability in growth response to light across climatic regions in northwestern British Columbia. Can. J. For. Res. 28:871–886.

Young-Robertson, J.M., W.R. Bolton, U.S. Bhatt, J. Cristóbal, and R. Thoman. 2016. Deciduous trees are a large and overlooked sink for snowmelt water in the boreal forest. Sci. Rep. 6, 29504. Available at http://www.nature.com/srep.

APPENDIX 1 Climate station and microclimate monitoring

TABLE A1-1 *Description of equipment, equipment location, and data output for open climate stations at the Bednesti research site (Bednesti North and Bednesti South) during the periods 1988–1990, 1992, 1993–1997, 1998, and 1999–2017*

Time period	Station location	Measurement variable	Position (cm)[a]	Reps	Sensor make/model	Sensor type	Other information	Output
1988 - 1990	Bednesti South Directional study Plot 3G	Air temperature	+130 - 150	1	Campbell Scientific/207	Thermistor	Shielded in Stevenson screen	Daily avg, max, min
		Relative humidity	+130 - 150	1	Campbell Scientific/207	Humidity chip	Shielded in Stevenson screen	
		Windspeed	Unknown (~+200)	1	Lakewood Systems/LE8520	Cup anemometer		
		Rainfall	+60	1	Sierra Misco/2501	Tipping bucket		Daily total
		Solar radiation	+200	1	Li-Cor/LI200S	Silicon pyranometer	Serial #7103	
1992	Unknown; may still have been in Plot 3G, but equipment changed	Air temperature	+130 - 150	2	Campbell Scientific/107	Thermistor	Shielding unknown	Daily avg, max, min
		Rainfall	+60	1	Sierra Misco/2501	Tipping bucket		Daily total
		Solar radiation	+200		Li-Cor/LI200S	Silicon pyranometer	Sensor height estimated based on assumed shielding by Stevenson screen	
1993 - 1997	Unknown; possibly same location as 1992, or could have been in Madge experiment	Air temperature	+20	1	Campbell Scientific/107	Thermistor	Assumed unshielded	Daily max, min
		Air temperature	+130 - 150	1	Campbell Scientific/207	Thermistor	Shielded in Stevenson screen 1993; other years unknown	
		Relative humidity	+130 - 150	1	Campbell Scientific/207	Humidity chip		
		Rainfall	+60	1	Sierra Misco/2501	Tipping bucket		Daily total
1998	Unknown	Air temperature	+130 - 150	1	Campbell Scientific/207	Thermistor	Shielded in Stevenson Screen	Daily avg, max, min
		Relative humidity	+130 - 150	1	Campbell Scientific/207	Humidity chip	Shielded in Stevenson Screen	
		Rainfall	+60	1	Sierra Misco/2501	Tipping bucket		Daily total
		Solar radiation	+200	1	Li-Cor/LI200S	Silicon pyranometer		Daily total
		Soil temperature	-2.5	2	Unknown	Unknown		Daily avg, max, min
			-15	1	Unknown	Unknown		
		Soil water potential	-2.5	2	Unknown	Gypsum blocks		
			-15	1	Unknown	Gypsum blocks		

TABLE A1-1 *Continued*

Time period	Station location	Measurement variable	Position (cm)[a]	Reps	Sensor make/model	Sensor type	Other information	Output
1999 - 2017	Bednesti North experiment: Untreated area immediately east of plot C1[b]	Air temperature	+130 (centre)	2	Home built/ fine wire 36 awg	Type T thermocouple[d]	Unshielded	Daily: avg, max, min; Hourly: avg
			+300 (centre)	2				
			+130 (edge)	1	Campbell Scientific/HMP 35C	Thermistor	Shielded with Gill plate	
		Relative humidity	+130 (edge)	1	Campbell Scientific/HMP 35C	Capacitive chip	Shielded with Gill plate	
		Rainfall	+60 (centre)	1	Sierra Misco/2501	Tipping bucket		Daily: total, avg, max, min; Hourly: avg
		Solar radiation	+300 (centre)	1	Li-Cor/LI200S	Silicon pyranometer	Serial # 29613	Daily: avg, max, min; Hourly: avg
		PAR[c]	+300 (centre)	1	Kipp & Zonen/PARlite	Quantum sensor	Serial # KZ050557	
		Soil temperature	-2.5	3	Home built/twisted soldered wire	Type T thermocouple[d]		Daily: avg, max, min; Hourly: avg
			-15	3				
			-50	3				
		Soil water potential	-2.5	3	Campbell Scientific/223	Gypsum block		Daily: sample
			-15	3				
			-50	3				
			-15	3		Gypsum block	new 2011	
			-15	2		Gypsum block	new 2012	
			-15	5	Campbell Scientific/253	Granular matrix resistance sensor	new 2017	
		Soil volumetric water content	-15	1	Campbell Scientific/CS615	TDR		Daily: avg; Hourly: avg

[a] Values for height (+) indicate height (cm) above the ground surface (regardless of whether mineral soil or organic material). Values for soil depth (-) indicate depth from the mineral soil/forest floor interface. For the period 1999–2017, edge or centre indicate position in the 20 x 25 m opening.

[b] Climate station located in opening approximately 20 x 25 m that is maintained free of tall vegetation by annual brushing. By 2017, trees surrounding the opening were up to 14 m tall, resulting in considerable early- and late-day shading.

[c] PAR is photosynthetically active radiation. PAR was measured with a Kipp & Zonen sensor except for the period of May–September 2012 when a Li-Cor sensor, model L1190 (serial #Q39488) was substituted.

[d] Type T is copper-constantan.

TABLE A1-2 *Measurement years and notes regarding data reliability at the open climate stations (colours correspond to time periods designated in Table A1-1)*

	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Year post-planting	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Air temperature	x	x	x		x	x	x^2	x^2	x^2	x	x	x^1	x^1	x^1	x^1	x^1	x^1	x^1	x^1	x^1	x^1	x^1	x^1	x	x	x	x	x	x	x
Relative humidity	x	x	x						x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Rainfall	x	x	x		x	x	x	x	x	x	x^1	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Windspeed	x	x																												
Solar radiation	x	x	x		x						x^1	x	x	x^1	x^1	x^1	x^1	x^1	x^1	x^1	x^1	x^1	x^1	x^1	x^1	x^1	x^1	x^1	x^1	x^1
PAR																			x	x	x	x	x	x	x^1	x	x	x^1	x^1	x
Soil temperature												x^1	x^1	x^1	x^1	x^1	x^1	x^1	x^1	x^1	x^1	x^1	x^1	x	x	x	x	x	x	x
Soil water potential (1999 installed gypsum blocks)												x	x	x	x	x	x^3	x^2	x^2	x^2	x^2	x^3	x^3	x^3	x^3	x^3	x^3	x^3	x^3	
Soil water potential (2011 installed gypsum blocks)																								x	x	x	x	x	x^2	x^3
Soil water potential (2012 installed gypsum blocks)																									x	x	x	x	x	x^2
Soil water potential (2017 installed granular matrix resistance sensors)																														x^1
Soil volumetric water content															x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x

NOTES on above measurements (x = good data; x^1 = see data notes which may affect data interpretation; x^2 = data quality questionable; x^3 = data bad, do not use)

Air temperature	
1994	Some bad data July and August; daily mean temperature readings too high in comparison to nearby MSC stations; possible shielding problem.
1995	Intermittent bad data noted on minimums; daily mean temperature readings are too high in comparison to nearby MSC stations; shielding problem.
1996	Intermittent bad data noted on minimums.
1999 - 2010	Measurements at opening edge are good because a shielded thermistor was used. For thermocouple measurements in centre of opening, CR10 internal temperature was used as a reference for thermocouple measurements from 1999 until 29 June 2010 when panel reference temperature was installed. There are likely significant errors to daily maximum and minimum temperatures and hourly average temperatures.
Rainfall	
1998	Numbers too small due to incorrect mutiplier. Data values need to be multiplied by 4.
Solar radiation	
1998	Bad data during the period 1-30 May 1998; reversed polarity on datalogger panel gives negative output for period 31 May to 2 Oct 1998.
2001 - 2017	Not calibrated since at least 1999 when installed. On 31 May 2017, sensor s/n 29613 was removed for recalibration and replaced with sensor s/n 29612.
PAR	
2012	Kipp & Zonen/PARlite (s/n KZ050557) sensor was removed for calibration from 30 May 2012 to 24 Sep 2012; during this period it was replaced with a Li-Cor/LI190 sensor (s/n Q39488).
2015	Kipp & Zonen/PARlite (s/n KZ050557) sensor was removed for calibration on 21 May 2015 and replaced with Kipp & Zonen/PARlite (s/n KZ000098).
2016	Kipp & Zonen/PARlite (s/n KZ000098) was removed and replaced with recalibrated Kipp & Zonen/PARlite (s/n KZ050557).
Soil temperature	
1999 - 2010	CR10 internal temperature was used as a reference for thermocouple measurements from 1999 until 29 June 2010 when panel reference temperature was installed. There will be significant errors to daily maximum and minimum temperatures as well as hourly average temperatures.
Soil water potential	
Gypsum blocks installed in 1999	
2004 - 2008	Gypsum blocks installed in 1999 are at the end of their expected useful lifespan. Data quality is questionable.
2009 - 2016	Gypsum blocks installed in 1999 are well beyond their useful life. Data quality is bad. Monitoring of the gypsum blocks installed in 1999 was discontinued after 2016.
Gypsum blocks installed in 2011	
2016	Gypsum blocks installed in 2011 are at the end of their expected useful lifespan. Data quality is questionable.
2017	Gypsum blocks installed in 2011 are beyond their useful life. Data quality is bad.
Gypsum blocks installed in 2012	
2017	Gypsum blocks installed in 2012 are at the end of their expected useful lifespan. Data quality is questionable.
Granular matrix resistance sensors installed in 2017	
2017	These sensors only have effective range of 0 to -2 Bar compared with gypsum blocks that have a range of 0 to -15 Bar.

TABLE A1-3 *Description of equipment, equipment location, and data output for microclimate monitoring at the Bednesti North research site during the periods 1988–1990 and 1999–2017 (data were not collected in other periods)*

Time period	Treatment	Measurement variable	General position	Height or depth (cm)[a]	Reps	Sensor make/model	Sensor type	Other information (MS=mineral soil; FF=forest floor)	Output
1988 - 1990	Bräcke mound	Soil temperature	Mound	-10	4	Campbell Scientific/101	Thermistor		Hourly max, min, sample
			Mound	-20	4				
		Soil water potential	Mound	-10	4	Unknown	Gypsum block	Not measured by datalogger	Weekly sample
			Mound	-20	4				
	Bräcke patch	Soil temperature	Shoulder	-10	4	Campbell Scientific/101	Thermistor		Hourly max, min, sample
		Soil water potential	Shoulder	-10	4				
	Bedding plow	Soil temperature	Seedling # 174	-10	1	Campbell Scientific/101	Thermistor	Original MS surface at 10 cm depth	Hourly max, min, sample
				-20	1				
			Seedling # 176	-10	1	Campbell Scientific/101	Thermistor	Original MS surface at 10 cm depth	Hourly max, min, sample
				-20	1				
			Seedling # 183	-10	1	Campbell Scientific/101	Thermistor	Original MS surface at 17 cm depth so 10 cm probe primarily in FF material	Hourly max, min, sample
				-20	1				
			Seedling # 191	-10	1	Campbell Scientific/101	Thermistor	Original MS surface at 17 cm depth so 10 cm probe primarily in FF material	Hourly max, min, sample
				-20	1				
		Soil water potential	Seedling # 174	-10	1	Unknown	Gypsum block	Not measured by datalogger; notes relating to thermistor depth (above) also apply to gypsum blocks	Weekly sample
				-20	1				
			Seedling # 176	-10	1				
				-20	1				
			Seedling # 183	-10	1				
				-20	1				
			Seedling # 191	-10	1				
				-20	1				
	Wadell trenching	Soil temperature	Seedling # 110	-10 berm	1	Campbell Scientific/101	Thermistor	Mound top and original FF at 15 cm depth; 10 cm mound probe above FF	Hourly max, min, sample
				-10 trench	1				
			Seedling # 112	-10 berm	1	Campbell Scientific/101	Thermistor	10 cm mound probe just below original FF	Hourly max, min, sample
				-10 trench	1				
			Seedling # 119	-10 berm	1	Campbell Scientific/101	Thermistor	MS depth 11 cm; 10 cm probe just above FF	Hourly max, min, sample
				-10 trench	1				
			Seedling # 120	-10 berm	1	Campbell Scientific/101	Thermistor		Hourly max, min, sample
				-10 trench	1				
			Control	-10	4	Campbell Scientific/101	Thermistor	Control is between trenches	Hourly max, min, sample

TABLE A1-3 *Continued*

Time period	Treatment	Measurement variable	General position	Height or depth (cm)[a]	Reps	Sensor make/model	Sensor type	Other information (MS=mineral soil; FF=forest floor)	Output
1988 - 1990	Wadell trenching	Soil water potential	Seedling # 110	-10 berm	1	Unknown	Gypsum block	Not measured by datalogger; notes relating to thermistor depth (above) also apply to gypsum blocks	Weekly sample
				-10 trench	1				
			Seedling # 112	-10 berm	1				
				-10 trench	1				
			Seedling # 119	-10 berm	1				
				-10 trench	1				
			Seedling # 120	-10 berm	1				
				-10 trench	1				
			Control	-10	4				
	Breaking plow	Soil temperature	Unknown	-10	4	Campbell Scientific/101	Thermistor	Sensor placement details unknown	Hourly, max, min
				-20	3				
		Soil water potential	Unknown	-10	4	Unknown	Gypsum block	Not measured by datalogger	Weekly sample
				-20	4				
1999 - 2017	Delta hinge (Plot C1)[b]	Air temperature		+130	2	Home built/fine wire 36 awg	Type T thermocouple[c]	Unshielded	Daily avg, max, min; Hourly avg
				+300	2				
		Soil temperature	Untreated area between trenches	-2.5	3	Home built/twisted soldered wire	Type T thermocouple[c]		Daily avg, max, min; Hourly avg
				-15	3				
				-50	3				
			High on berm	-2.5	3				
		Soil water potential	Untreated area between trenches	-2.5	3	Campbell Scientific/223	Gypsum block		Daily sample
				-15	3				
				-50	3				
			High on berm	-2.5	3				
			Untreated area between trenches	-15	3		Gypsum block	New in 2011	
				-15	2		Gypsum block	New in 2012	
				-15	5	Campbell Scientific/253	Granular matrix resistance sensor	New in 2017	
		Soil volumetric water content	Untreated area between trenches			Campbell Scientific/CS615	TDR		Daily avg; Hourly avg
2012 - 2017	Dense aspen stand (plot A2)	Soil water potential		-15	4	Campbell Scientific/227	Gypsum block		Daily avg, max, min; Hourly sample
		Soil volumetric water content		-15	1	Campbell Scientific/CS616	TDR		Daily avg, max, min; Hourly sample
		PAR		+100	1	Kipp & Zonen/ PARlite			Daily avg, max, min; Hourly avg
	Semi-open aspen stand (S of plot A2)	Rainfall		+75	1	Texas elec/TE25mm	Tipping bucket		Daily total; hourly total

[a] Values for height (+) indicate height (cm) above the ground surface (mineral soil or organic material). Values for depth of soil sensors (-) indicate depth from the mineral soil/forest floor interface for control treatments and from the ground surface (mineral soil or organic material) for site preparation treatments.

[b] Delta hinge treatment (aka disc trench hinge treatment). In plot C1, all measurements except volumetric water content were made using a single CR10X/multiplexor combination. Volumetric water content was measured using a separate CR10 datalogger.

[c] Type T is copper-constantan.

TABLE A1-4 *Measurement years and notes regarding data reliability for microclimate monitoring at the Bednesti North site (colours correspond to time periods designated in Table A1-3)*

		1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
	Year post-planting	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**
Air temperature	Delta hinge												x[1]	x[1]	x[1]	x[1]	x[1]	x[1]	x[1]	x[1]	x[1]	x[1]	x[1]	x[1]	x	x	x	x	x	x	x
Soil temperature	Bräcke mound	x	x																												
	Bräcke patch	x	x																												
	Bedding plow	x	x	x																											
	Wadell trenching	x	x																												
	Breaking plow	x	x																												
	Delta hinge												x[1]	x[1]	x[1]	x[1]	x[1]	x[1]	x[1]	x[1]	x[1]	x[1]	x[1]	x[1]	x	x	x	x	x	x	x
Soil water potential	Bräcke mound	x	x																												
	Bräcke patch	x	x																												
	Bedding plow	x	x	x																											
	Wadell trenching	x	x																												
	Breaking plow	x	x																												
Soil water potential (1999 gypsum blocks)	Delta hinge (plot C1)												x	x	x	x	x	x[2]	x[2]	x[2]	x[2]	x[2]	x[3]	x[3]	x[3]	x[3]	x[3]	x[3]	x[3]	x[3]	
Soil water potential (2011 gypsum blocks)	Delta hinge (plot C1)																								x	x	x	x	x	x[2]	x[3]
Soil water potential (2012 gypsum blocks)	Delta hinge (plot C1)																									x	x	x	x	x	x[2]
	Dense aspen (plot A2)																									x	x	x	x	x	x[2]
Soil water potential (2017 installed granular matrix resistance sensors)	Delta hinge (plot C1)																														x[1]
Soil volumetric water content	Delta hinge (plot C1)																	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Dense aspen (plot A2)																									x	x	x	x	x	x
PAR	Dense aspen (plot A2)																									x	x	x	x	x	x
Rainfall	Semi-open aspen (S of plot A2)																									x	x	x	x	x[1]	

NOTES on above measurements (x = good data; x[1] = see data notes which may affect data interpretation; x[2] = data quality questionable; x[3] = data bad, do not use)

Air temperature

1999 - 2010 CR10 internal temperature was used as a reference for thermocouple measurements from 1999 until 29 June 2010 when panel reference temperature was installed. There are likely significant errors to daily maximum and minimum temperatures and hourly average temperatures.

Soil temperature

1988 - 1990 Original raw data is missing. Data were compiled into daily averages by replicate.

1999 - 2010 CR10 internal temperature was used as a reference for thermocouple measurements from 1999 until 29 June 2010 when panel reference temperature was installed. There are likely significant errors to daily maximum and minimum temperatures and hourly average temperatures.

Soil water potential

Gypsum blocks installed 1999

2004 - 2008 Gypsum blocks installed in 1999 are at the end of their expected useful lifespan. Data quality is questionable.

2009 - 2016 Gypsum blocks installed in 1999 are well beyond their useful life. Data quality is bad.

Gypsum block installed 2011

2016 Gypsum block installed in 2011 is at the end of its expected useful lifespan. Data quality is questionable.

2017 Gypsum block installed in 2011 is beyond its useful life. Data quality is bad.

Gypsum block installed 2012

2017 Gypsum block installed in 2012 is at the end of its expected useful lifespan. Data quality is questionable.

Granular matrix resistance sensors installed in 2017

2017 These sensors only have effective range of 0 to -2 Bar compared with gypsum blocks that have a range of 0 to -15 Bar.

Rainfall

2016 Rain gauge removed 25 May 2016.

TABLE A1-5 *Description of equipment, equipment location, and data output for microclimate monitoring at the Bednesti South study site during the periods 1988–1990 and 1993–1997 (data were not collected in other years)*

Time period	Station location	Measurement variable	General position	Height or depth (cm)[a]	Reps	Sensor make/model	Sensor type	Other information (MS=mineral soil; FF=forest floor)	Output
1988 - 1990	Madge study	Soil temperature	Madge	-10	4	Campbell Scientific/101	Thermistor	Control sensor in adjacent untreated area	Hourly max, min
			Control	-10	3				
		Soil water potential	Madge	-10	4	Unknown	Gypsum block	Not measured by datalogger	Weekly sample
			Control	-10	3				
	Directional disc trenching study (E - W oriented disc trenching in Plot 3Y)	Soil temperature	Hinge S aspect	-10	4	Campbell Scientific/101 (1 of 2 in this treatment plot)	Thermistor	Probes at seedlings 331, 332, 333, 341	Hourly max, min, sample
			Hinge N aspect	-10	4		Thermistor	Probes at seedlings 327, 328, 336, 337	Hourly max, min, sample
			Top of berm	-10	4		Thermistor	Probes at seedlings 331, 332, 336, 337	Hourly max, min, sample
			Untreated area between trenches	-10	4	Campbell Scientific/101 (2 of 2 in this treatment plot)	Thermistor	Probes at seedlings 168, 169, 174, 175	Hourly max, min, sample
			Mineral mound in furrow bottom	-10	4		Thermistor	Probes at seedlings 331, 332, 336, 337	Hourly max, min, sample
			Furrow bottom	-10	4		Thermistor	Probes at seedlings 331, 332, 336, 337	Hourly max, min, sample
		Soil water potential	Hinge S aspect	-10	4	Unknown	Gypsum block	Not measured by datalogger; gypsum blocks located with soil temperature thermistors as described above	Weekly sample
			Hinge N aspect	-10	4				
			Top of berm	-10	4				
			Untreated area between trenches	-10	4				
			Mineral mound in trench	-10	4				
			Furrow bottom	-10	4				
	Directional disc trenching study N - S oriented disc trenching in Plot 3G	Soil temperature	Hinge E aspect			Campbell Scientific/101 (1 of 2 in this treatment plot)	Thermistor	Probes at seedlings 736, 737, 767, 797	Hourly max, min, sample
			Hinge W aspect	-10	4		Thermistor	Probes at seedlings 720, 748, 776, 777	Hourly max, min, sample
			Top of berm	-10	4		Thermistor	Probes at seedlings 737, 748, 777, 797	Hourly max, min, sample
			Untreated area between trenches	-10	4	Campbell Scientific/101 (2 of 2 in this treatment plot)	Thermistor	Probes at seedlings 363, 380, 381, 390	Hourly max, min, sample
			Mineral mound in furrow bottom	-10	4		Thermistor	Probes at seedlings 737, 748, 767, 777	Hourly max, min, sample
			Furrow bottom	-10	4		Thermistor	Probes at seedlings 736, 748, 767, 776	Hourly max, min, sample
		Soil water potential	Hinge E aspect	-10	4	Unknown	Gypsum block	Not measured by datalogger; gypsum blocks located with soil temperature thermistors as described above	Weekly sample
			Hinge W aspect	-10	4				
			Top of berm	-10	4				
			Untreated area between trenches	-10	4				
			Mineral mound in furrow bottom	-10	4				
			Furrow bottom	-10	4				
1993 - 1997	Madge study	Air temperature	Unknown	+2	1	Unknown	Unknown		Daily max, min
		Soil temperature	Madge	-2	2	Unknown	Thermistors assumed	Interface occurs at the depth where the Madge disturbance meets undisturbed soil	Daily max, min
			Interface	-	2				
			Control	-2	1				
				-15	1				
		Soil water potential	Madge	-2	1	Unknown	Gypsum block		Daily max, min

[a] Values for height (+) indicate height (cm) above the ground surface (mineral soil or organic material). Values for depth of soil sensors (-) indicate depth from the mineral soil/forest floor interface for control treatments and from the ground surface (mineral soil or organic material) for site preparation treatments.

TABLE A1-6 *Measurement years and notes regarding data reliability for treatment microclimate monitoring at the Bednesti South site (colours correspond to time periods designated in Table A1-5)*

				Year and year post-planting																																
		Treatment	**Height/depth**	**1988**	**1989**	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
				1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**
Air temperature	Madge study	Unknown	All						x	x^2	x^2	x	x																							
Soil temperature	Madge study	Madge	-2	x	x	x			x^2	x^2	x^2	x^2	x																							
			Interface						x^2	x^2	x^2	x^2	x																							
		Control	-2						x^2	x^2	x^2	x	x																							
			-15						x^2	x^2	x^2	x^3	x^3																							
	Directional study	E-W trenching	All	x	x	x																														
		N-S trenching	All	x	x																															
Soil water potential	Madge study	Madge	All	x	x																															
	Directional study	E-W trenching	All	x	x	x																														
		N-S trenching	All	x	x																															

NOTES (x = good data; x^1 = see data notes which may affect data interpretation; x^2 = data quality questionable; x^3 = data bad, do not use)

Air temperature	
1993 - 1997	Maximum temperatures >40°C suggest sensor may have been unshielded.
Soil temperature	
1988 - 1990	Original raw data are missing. Data were compiled into daily averages by replicate.
1993 - 1997	Frequent intermittent bad data for daily minima until April 1996.

TABLE A1-7 *Description of equipment and sensor depth for the Bednesti mound soil temperature study (1997–1998)*[a]

Mound type[b]	Material	Position in material	Position name in data files	Reps	Sensor make/model	Sensor type	Output
20 cm inverted mounds (100 cm wide x 100 cm long)	Mineral cap	-2.5	2.5cm	1	Unknown	Unknown	Daily avg, max, min; Hourly avg
		-10	10cm	1			
		-20	20cm	1			
	Organic	Inversion interface	20cm organic	1			
	Undisturbed mineral	-2.5	20+2.5	1			
		-15	20+15	1			
14 cm inverted mounds (60 cm wide x 60 cm long)	Mineral cap	-2.5	2.5cm	1	Unknown	Unknown	Daily avg, max, min; Hourly avg
		-10	10cm	1			
		-14	14cm	1			
	Organic	Inversion interface	14cm organic	1			
	Undisturbed mineral	-2.5	14+2.5	1			
		-15	14+15	1			
14 cm mineral mounds (60 cm wide x 60 cm long)	Mineral cap	-2.5	2.5cm	1	Unknown	Unknown	Daily avg, max, min; Hourly avg
		-10	10cm	1			
		-14	14cm	1			
	Undisturbed mineral	-2.5	14+2.5	1			
		-15	14+15	1			
6 cm inverted mounds (30 cm wide x 30 cm long)	Mineral cap	-2.5	2.5cm	1	Unknown	Unknown	Daily avg, max, min; Hourly avg
		-6	6cm	1			
	Organic	Inversion interface	6 cm organic	1			
	Undisturbed mineral	-2.5	6+2.5	1			
		-15	6+15	1			
Control	Undisturbed mineral	-2.5	2.5cm	1	Unknown	Unknown	Daily avg, max, min; Hourly avg
		-15	15cm	1			

[a] All the above variables were assessed in both 1987 and 1988 and all data were good.

[b] Inverted mounds include forest floor and mineral capping inverted over undisturbed forest floor material; mineral mounds are composed of mineral soil piled on exposed mineral material; mounds are located between Bednesti North plots B3 and B4; the control is undisturbed soil adjacent to the mounds.

Quality Check of Air Temperature and Precipitation Data

To check for quality and consistency, air temperature and rainfall data were compared with data from two nearby ECCC stations. The Vanderhoof station (1980–2017, climate ID 1098D90) is located 39.5 km west-northwest of the Bednesti study site, at an elevation of 638 m, and the Miworth station (1984–2002, climate ID 1096465) is located 37.6 km to the east-northeast of the Bednesti site at an elevation of 610 m. Both these stations are located in the Nechako River valley, and are approximately 200 m lower in elevation than the Bednesti site, which is at an elevation of 850 m.

Daily mean growing-season (May–September) air temperatures were plotted for each year from 1988 to 2014 to compare the three stations (Miworth ceased collecting data in 2002) to check for consistency. It was assumed that data collection methods at the ECCC stations remained consistent throughout the period; therefore, any abrupt changes in the magnitude of differences between these stations and Bednesti would be indicative of a change in methodology or sensor type at Bednesti. Daily mean air temperature was consistently 1–2.5°C lower at Bednesti than at the nearby ECCC stations. The exceptions to this were the 1994 and 1995 growing seasons, when daily mean air temperatures at Bednesti were as much as 5°C higher than those of the ECCC stations. This suggests that the sensor at Bednesti was either not properly shielded from solar radiation, or that some other sensor problem existed. These data were discarded and replaced with data generated using a linear regression with Vanderhoof data. Other data gaps in the Bednesti record were also filled with regression-generated data. Overall, about 47% of the May–September daily air temperature data for the period 1988–1995 was generated using linear regressions with Vanderhoof data. Most of this was due to missing data for 1991 and faulty data for the 1994 and 1995 seasons. Only 1.5% of the May–September data for the period 1996–2015 needed to be filled in with values generated by linear regression.

Seasonal rainfall totals were also compared among the Bednesti, Vanderhoof, and Miworth weather stations for the period 1988–2017 (Figure A2-1). Some of these totals do not represent all precipitation

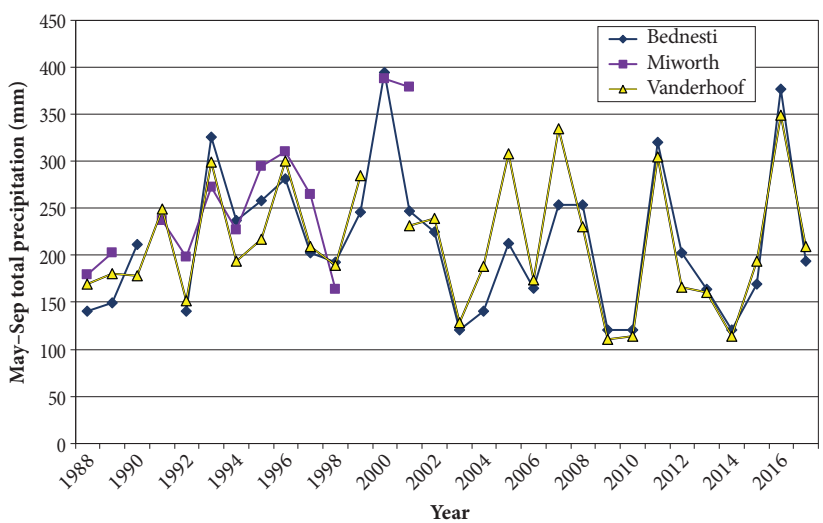

FIGURE A2-1 *Comparison of seasonal measured precipitation totals for the period 1988–2017 at the Bednesti study site, the Vanderhoof ECCC station, and the Miworth ECCC station. Within a given season, daily precipitation amounts were added to the totals only when data were present for all sites.*

recorded at a given station because, to allow for comparison, data were eliminated for dates where it was not available from all three stations. Seasonal totals were generally comparable among the three stations, with the Vanderhoof–Bednesti relationship (R^2=0.74) being somewhat better than the Miworth–Bednesti relationship (R^2=0.61). Missing data at Bednesti were therefore replaced with daily totals from Vanderhoof. We recognize that daily rainfall totals for the two locations may be quite different due to the spotty nature of summer convective precipitation events. These differences, however, tend to average out when seasonal totals are calculated. Overall, for the period 1988–2015, 11.5% of the Bednesti daily precipitation data was bad or missing. It also can reasonably be assumed that winter precipitation at Bednesti was well-correlated with that at the Vanderhoof station; winter precipitation tends to be associated with large-scale weather systems affecting large geographic areas, so there is likely to be better correspondence between Bednesti and Vanderhoof precipitation in the winter than in the summer. Winter precipitation data were not collected at Bednesti; so, consequently, we used Vanderhoof winter precipitation data for purposes of this analysis.

Thermocouple Reference Temperature: Effects on Temperature Measurements of Using CR10X Internal Temperature Instead of Panel Temperature

Beginning when the climate stations were installed in 1999, soil and air thermocouple temperatures were determined using CR10X internal temperature as a reference temperature. However, this internal temperature measurement was made on the CR10X circuit board rather than on the datalogger wiring panel, where reference temperature is ideally measured. This was later determined to be a source of error in the thermocouple measurements because internal temperature tends to lag behind the temperature of the panel due to the thermal inertia of the datalogger module. On 29 June 2010, a reference temperature thermistor (Campbell Scientific, Model CR10XTCR) was installed on the CR10X wiring panel. Copper and constantan wires were used to connect the multiplexor common terminals to the analog measurement datalogger channel. This enabled the reference temperature to be measured on the datalogger panel, even though thermocouple sensor wires were connected to the multiplexor wiring panel. The datalogger program was modified so that thermocouple temperatures could be determined using both CR10X internal temperature and panel temperature. This allowed comparison of thermocouple temperatures that had been determined by both approaches for the 2010–2015 period. This comparison makes it possible to assess the earlier (1999–2010) errors in thermocouple measurements that were made when only CR10X internal temperature was used as a reference.

Total growing-season growing degree-days (GDDs) (both soil and air) are underestimated by 1–2% when CR10 internal temperature is used as a reference. The average difference between daily minimum air temperatures determined using the CR10 temperature and that determined using the panel reference temperature at Bednesti during the period of 2010–2015 was approximately 0.5°C (i.e., air temperature determined using the CR10 temperature was too high). Maximum differences during the growing season were typically 0.8–1.0°C. When hourly data were examined, it was found that differences were greatest when the daily minimum air temperature occurred in the evening as temperatures were dropping rapidly (i.e., when the CR10X internal temperature was most different from, and lagged furthest behind, the panel temperature). Examination of data collected from 2010–2015 at Bednesti revealed that there were from one to 10 instances per growing season when minimum air temperatures determined using the panel temperature were just below freezing (0 to -0.7°C) while those determined

using the CR10 temperature were above freezing. In consequence, the number of frosts per growing season was likely underestimated for air temperature determined using CR10 internal temperature as a reference. This is also likely to have affected determination of the frost-free period, with the largest errors resulting from the occurrence of frost events in the middle of the growing season.

For the purpose of results presented in this publication, the errors in total growing-season soil and air GDDs were judged to be small enough to ignore. Daily minimum and hourly average air temperatures were corrected for the period 1999–2009 using linear regressions derived from the 2010–2015 data. These corrections allow for a more accurate assessment of the frost-free period and the number of hours below freezing during the growing season.

APPENDIX 3 Measurement dates for lodgepole pine seasonal growth measurements 1992–1994 in the Bednesti North experiment

Year	Date	Treatments[a]											
		Disc trench hinge		Coarse mixing		Plow inverting		Patch scarification		Burned windrow		Untreated control	
		H[b]	D[b]	H	D	H	D	H	D	H	D	H	D
1992	May 17	x	x	x	x	x	x	x	x	x	x	x	x
	June 2	x	x	x	x	x	x	x	x	x	x	x	x
	June 16	x	x	x	x	x	x	x	x	x	x	x	x
	July 1	x	x	x	x	x	x	x	x	x	x	x	x
	July 16	x	x	x	x	x	x	x	x	x	x	x	x
	August 1	x	x	x	x	x	x	x	x	x	x	x	x
	August 16	x	x	x	x	x	x	x	x	x	x	x	x
	September 1	x	x	x	x	x	x	x	x	x	x	x	x
	September 17	x	x	x	x	x	x	x	x	x	x	x	x
	October 1		x		x		x		x		x		x
1993	April 25		x		x						x		x
	May 15	x	x	x	x					x	x	x	x
	June 1	x	x	x	x					x	x	x	x
	June 15	x	x	x	x					x	x	x	x
	July 1	x	x	x	x					x	x	x	x
	July 16	x	x	x	x					x	x	x	x
	August 1	x	x	x	x					x	x	x	x
	August 15	x	x	x	x					x	x	x	x
	September 1	x	x	x	x					x	x	x	x
	September 15	x	x	x	x					x	x	x	x
	September 30	x	x	x	x					x	x	x	x
	October 14	x	x	x	x					x	x	x	x
1994	April 15		x		x						x		x
	May 1	x	x	x	x					x	x	x	x
	May 15	x	x	x	x					x	x	x	x
	June 1	x	x	x	x					x	x	x	x
	June 15	x	x	x	x					x	x	x	x
	July 1	x	x	x	x					x	x	x	x
	July 15	x	x	x	x					x	x	x	x
	July 31	x	x	x	x					x	x	x	x
	August 14	x	x	x	x					x	x	x	x
	August 31	x	x	x	x					x	x	x	x
	October 2	x	x	x	x					x	x	x	x
	October 16		x		x						x		x

[a] Refer to McClarnon et al. (2016) for treatment descriptions.

[b] H is height; D is diameter

APPENDIX 4 Proposed evapotranspiration (ET) index based on using hourly measurements of θ_v to assess daytime drawdown

As a way of quantifying the strength of the diurnal cycle of soil moisture content (θ_v) drawdown and recharge seen in Figure 16, we defined an index of evapotranspiration (I_{ET}). The index is computed simply by subtracting the daily minimum of hourly θ_v from the daily maximum of hourly θ_v. The index does not give a meaningful value during periods when there is significant gravity flow of water, such as during spring snowmelt or during and immediately after large rainfall events.

Figure A4-1 shows I_{ET} for April–September 2015. Spikes in the value greater than 0.0075 are generally attributable to gravity drainage caused by either snowmelt or rainfall events. In 2015, the first discernible diurnal signal indicating ET occurred on 9 April. This was significantly earlier than most seasons, when the first discernible signal indicating ET occurred from late April to early May. The date of the first discernible diurnal variation in θ_v attributed to ET is determined by visual inspection of graphs showing hourly θ_v data plotted for 5-day periods. The signal related to the onset of ET was characterized by a decrease in θ_v during the day followed by some nighttime recovery. This signal can be masked by rapidly rising or falling water contents during the snowmelt and subsequent drainage of gravity water through the soil profile. A diurnal signal is sometimes observed due to freeze-thaw cycles, where θ_v increases rapidly during the day followed by a decline at night when lower temperatures slow or stop snowmelt. This signal is differentiated from that due to ET by observing that, instead of falling, θ_v rises during the day and then falls at night. The index of evapotranspiration (I_{ET}) was briefly high in early April before declining until late April, followed by a steady rise to

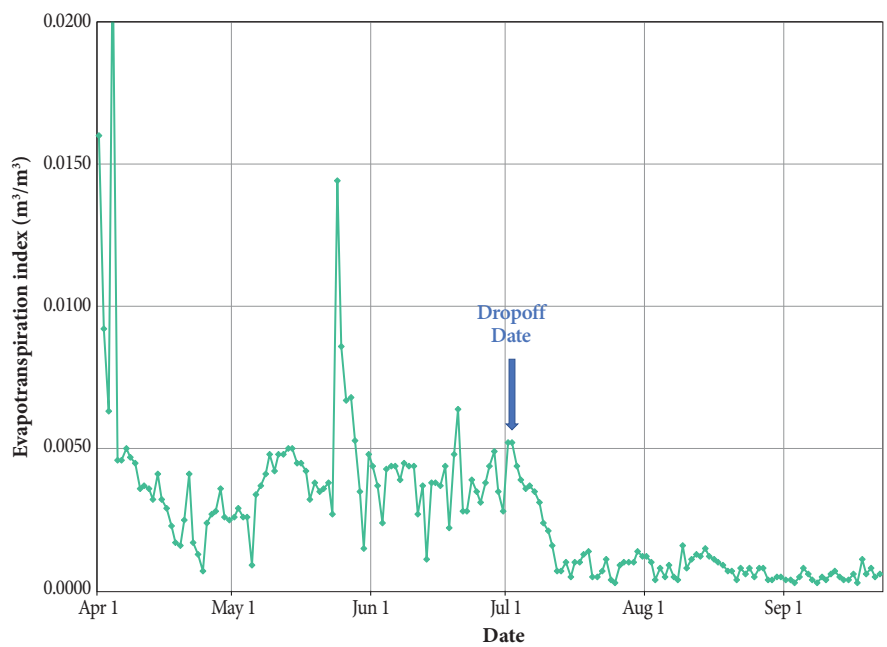

FIGURE A4-1 *Evapotranspiration index (I_{ET}) derived from hourly volumetric soil moisture content (θ_v) data for April–September 2015. Spikes in the slope value greater than 0.01 m^3/m^3 are generally attributable to gravity drainage caused by either snowmelt or rainfall events, and are not meaningful values of I_{ET}.*

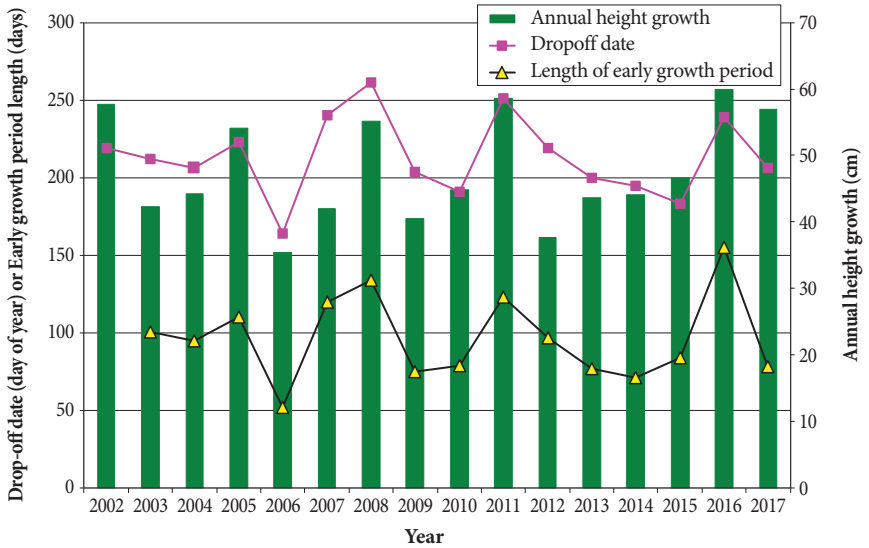

FIGURE A4-2 *Annual lodgepole pine height growth in plot C1, the volumetric soil moisture content (θ_v) drop-off date (day of year), and length of the early growth period for each year from 2002 to 2017.*

its maximum good value by mid-May. The value of I_{ET} was relatively steady for the period mid-May until early July, generally varying between 0.0025 and 0.01 m^3/m^3. The steep drop-off that began after 2 July corresponds with the time period shown in Figure 16. Similar drop-offs occur during most growing seasons, although these were difficult to discern during years with frequent rainfall events. Hereafter, we will call the date after which this decline in θ_v begins, and is followed by at least 10 days of lower I_{ET}, the "drop-off date," and the length of time between the first discernible diurnal ET signal and the drop-off date the "early growth period."

Figure A4-2 relates drop-off date and the length of the early growth period to the annual height growth increment in plot C1 for the 2002–2017 period. Both parameters seem to track the highs and lows of annual height growth increment. Structural time series analysis[4] and linear regression analysis were used to examine the relationship of four parameters related to soil moisture availability (number of days $\theta_v < 0.14 m^3/m^3$, mean θ_v, drop-off date, and length of the early growth period) with annual height growth. The small sample size (n=14) leads to relatively large standard errors, however the coefficient of determination (R^2) values suggest that height growth is related to each of the variables, with the relationship between the length of the early growth period and height growth being the strongest. Simple linear regression analysis, although it does not take into account trends of increasing annual height growth with age, indicated that the first three parameters explained 32–37% of the variation in annual height growth increment (Table A4-1). The length of the early growth period, which improves on drop-off date by taking into account that shoot elongation starts on different dates each year depending on a variety of factors, accounted for 43% of the variation in annual height growth. For example, the annual height growth for 2015 was slightly higher than that for 2013 and 2014, despite continued low growing-season soil moisture during 2015. This may

[4] Nemec, A.F.L. 2016. Preliminary analysis of annual variations in the height growth of trees in Plot C1 at the Bednesti site (unpublished report prepared for B.C. Ministry of Forests, Lands and Natural Resource Operations, Resource Practices Branch).

be attributed to the fact that ET began 3 weeks earlier in 2015 than it did in either of the previous two seasons.

TABLE A4-1 *Coefficient of determination, R^2, for the linear regression models predicting annual height growth at plot C1 with various parameters for the period 2002–2017, except 2003–2017 for the early growth period length*

Parameter	R^2
Number of days $\theta_v < 0.14 m^3/m^3$ (May–September)	0.32
Mean (June–September) θ_v	0.37
Drop-off date	0.36
Early growth period length	0.43