Effects of Alternative Forest Harvesting Strategies on Snowpack Dynamics and Seasonal Soil Moisture Storage in Alberta's Mountain Headwaters

by

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Abstract

Snowpack accumulation and melt dynamics, and soil moisture storage (SMS) play a critical role in regulating stressed regional water supplies in the southern Alberta Rockies. However, these processes are sensitive to impacts from forest cover losses by timber harvesting and associated land disturbance. While numerous studies have investigated effects of clearcut harvesting, few studies have evaluated the comparative effects of alternative forest-harvesting methods on spatial and temporal snowpack accumulation-melt and subsequent growing season soil moisture dynamics, resulting in a knowledge gap about how current alternative or new/novel strategies influence these key hydrological processes. Spatio-temporal patterns of snowpack accumulation/melt and SMS were assessed from 2016-2018 in the three sub-watersheds located in the Crowsnest Pass, Alberta that were harvested using three different forest-harvesting strategies (clear-cut with tree retention, strip-shelterwood, and partial cut harvesting). Snowpack and SMS were measured in each harvest and adjacent undisturbed forest stands using a series of linear transects. Snow depth and water equivalent (SWE) was measured every 14-21 days from the period of peak snowpack through snow disappearance, and SMS monitored at the same frequency thereafter using time domain reflectometry (TDR) to measure soil water storage at 0-20 cm and 20-60 cm depths. Differences in snowpack accumulation and melt and SMS were evaluated in the context of measured differences in microclimate and modeled solar radiation forcing. Results from this study showed peak snow accumulation increased by 43% in harvested strips, and 28% in the partial-cut relative to corresponding forested reserves, while snowpacks in north and south facing clearcut were either not different or significantly less. Differences in solar radiation due to slope orientation and shading by retained trees produced highly varied patterns of snow accumulation and melt creating within-harvest differences in snow disappearance timing of up to 20 days.

Subsequent seasonal SMS was also generally increased by harvesting due to reduced water losses from tree transpiration. However, the duration and magnitude of differences in SMS varied among harvests and soil layer depths over wet and dry years, which was attributed to differences in the ability of specific harvest cutting-patterns to moderate surface soil moisture losses. Across both study years, increased SMS after harvesting was greatest in SS (39%) followed by CC (~25% across both north- and south-facing hillslopes), and PC (~19%) for the two soil layers considered (0-20, and 20-60 cm). Results from this study demonstrate key differences in the comparative ability of specific patterns of tree retention to moderate spatial patterns of snow accumulation and melt and seasonal SMS, and strongly reinforce past research on the importance of interactions between forest cover, slope-orientation, and solar radiation in controlling spatial and temporal water-balance. These findings provide new information on relationships between alternative forest harvesting methods and snowpack and SMS dynamics needed to help evaluate integrated forest-water management strategies in this vital water supply region.

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Chapter 1: Introduction

Forested mountain headwaters on the eastern slopes of the Rocky Mountains are a critical source of water supplies that sustain regional economic and ecological integrity in Alberta (Emelko et al., 2011). Predominantly derived from spring snowmelt and spring and summer rains, runoff from these watersheds is strongly controlled by snow accumulation and melt, and soil moisture storage (SMS). Snow accumulation and melt are the dominant driver of annual streamflow regimes, while SMS strongly moderates runoff generation because antecedent soil moisture conditions determine threshold levels of snowmelt and rain needed to cause saturation excess and overland flow (Koster et al., 2010; Merz and Plate, 1997; Penna et al., 2011; Tromp-van Meerveld and McDonnell, 2006). For example, in the Oldman River watershed of southwestern Alberta snowmelt typically provides 70-90% of annual streamflow, sustaining regional water supplies by usage rates that can exceed 90% (Byrne et al., 2006). However, water resources and ecological functions sustained by these headwaters are vulnerable to cumulative pressures from climate change (Stewart, 2009; Clow, 2010), and extensive land-use disturbance including timber harvesting (Moore and Wondzell, 2005; Schelker *et al.*, 2013; Schnorbus and Alila, 2013) that impact hydrologic processes including spatial and temporal snowpack and SMS dynamics which collectively regulate runoff.

Climate change is forecasted to increase mean annual temperatures in western Canada by 1.5-3°C (DeBeer et al., 2016) potentially altering seasonal surface water availability due to lower snowpack accumulation and earlier timing of spring melt, as well as more prevalent drought conditions during the growing season (Berghuijs et al., 2014; Brown and Mote, 2009; DeBeer et al., 2016; Stewart, 2009). Currently timber harvesting is the largest source of anthropogenic forest disturbance on the eastern slopes of the Alberta Rockies (ABMI, 2017), with clearcutting accounting for over 97% of the annual area harvested provincially in Alberta (Alberta Agriculture and Forestry, 2017). Timber harvesting can impact runoff production because loss of forest cover alters processes controlling spatial and temporal SMS dynamics. While runoff is typically measured at the catchment or basin scale, spatial and temporal patterns of snow accumulation and melt, and SMS are controlled by the complex interaction of high order control by climate (temperature and precipitation) (DeBeer and Pomeroy, 2017; Lundquist et al., 2013) with localized factors including topography (slope, elevation, aspect), surficial geology/pedology, and forest cover (Andréassian, 2004; Dickerson-Lange et al., 2017; Niemeyer et al., 2016; Williams et al., 2009).

Forest structure and canopy cover alter spatial and temporal patterns of snowpack accumulation and melt and SMS by moderating the influence of canopy interception storage, solar energy balance, and wind exposure (Moore and Wondzell, 2005; Varhola *et al.*, 2010; Schelker *et al.*, 2013; Schnorbus and Alila, 2013), as well as soil-water loss from tree-transpiration (Bosch and Hewlett, 1982). Loss of forest cover reduces canopy interception storage, resulting in increased net precipitation in clearings compared to intact forest stands (Golding and Swanson, 1986; Hubbart et al., 2015; Schelker et al., 2013). However, tree removal may also enhance exposure of snow and soil surfaces to wind and solar insolation, increasing snow melt/ablation rates and soil-water losses from turbulent heat and vapor flux (Pomeroy and Granger, 1997; Redding et al., 2003). In snow-dominated watersheds, collective regulation of water-energy balance by these interactions strongly link the spatial and temporal coupling of snow accumulation and melt and seasonal SMS legacy (Kampf et al., 2015; Williams et al., 2009).

A large number of studies have shown that reductions in canopy interception and transpiration from clearcutting typically increase runoff generation because of increased snow accumulation and SMS (Adams et al., 1991; Bosch and Hewlett, 1982; Brown et al., 2005; Hubbart et al., 2007; Moore and Wondzell, 2005; Stednick, 1996; Stegman, 1996; Winkler et al., 2015). Reported effects from timber harvesting on catchment water yield are highly varied, with published studies reporting water yield increases after clearcut harvesting of 6 to 80 % (Hubbart et al., 2015; Moore and Wondzell, 2005; Stednick, 1996; Swanson et al., 1986). However, increases in runoff responses during the snowmelt freshet and large precipitation events may also be associated with increased peak flows (Schnorbus and Alila, 2013). Larger peak flows increase the potential for negative impacts from increased sedimentation and flooding including ecological and economic costs from damage to habitat, sensitive fisheries, and infrastructure (Green and Alila, 2012; Kuras *et al.*, 2012) though such effects have generally not been demonstrated though direct field observations. Higher frequency and variability of extreme weather events from climate change are anticipated to increases the probability of these events (Emelko et al., 2011). Additionally, coupled changes in the timing and rates of snowmelt may result in altered streamflow regimes that include decreased summer baseflows (Winkler et al., 2015). As a result, increased emphasis is being placed on the use of alternative strategies of forest harvesting that may reduce negative hydrologic impacts associated with conventional methods of clearcutting.

A considerable number of past studies have quantified differences in spatial and temporal patterns of snow accumulation and melt and SMS between forests and clearings/clearcuts, however effects from different harvesting strategies that incorporate differing spatial patterns of tree retention remain less well understood. Comparisons of existing research on the effects of alternative harvesting methods on either snowpack or SMS are limited by differing methodologies and physiographic settings where each were conducted, and because exceedingly few studies provide a direct comparison of more than one type of harvesting strategy in the same setting. While various studies describe the general influence of alternative harvesting strategies on spatial and temporal patterns of snow accumulation and melt (Winkler et al., 2005; Alexander et al., 1985; Golding and Swanson, 1985; Troendle and Ruess, 1977), and soil moisture storage (Gebhardt et al., 2014; Chin, 2009; Childs and Flint, 1987) separately, no studies (to my knowledge) have measured and comparted these factors directly together in the context of timber harvesting. Research that improves understanding of the influence of specific alternative timber harvesting strategies on snow accumulation and melt and SMS dynamics is necessary to accurately predict hydrologic effects from the use of these strategies for improved forest-watershed management in the context of climate change adaptation.

Research for this study was conducted in the Crowsnest Pass on the eastern slopes of the Rocky Mountains in southwestern Alberta. Low-order snow-dominated forested catchments that characterize this region are a vital source of regional water supplies, and provide key habitat for sensitive cold-water fisheries that include threatened Westslope Cutthroat Trout (*Oncorhynchus clarki lewisi*). However, ecosystem values and water resources in this area are increasingly stressed by seasonally scarcity and high public recreational usage demands (Byrne et al., 2006), as well as the cumulative effects from natural and anthropogenic forest disturbances including wildfire, insect outbreaks, and extensive timber harvesting. The watershed selected for this study has been the site of long-term research since 2004 (Silins et al., 2016), and provides an extensive record of pre-disturbance stream discharge and water quality data, which findings from this project will compliment. Sub-catchments in this watershed where this research was conducted offered broadly similar slope-orientations, surficial geology, and forest structure, providing an optimal setting in which to test and compare differences between alternative harvesting strategies.

Research for this thesis was conducted to assess the comparative effects of several specific alternative harvesting strategies on coupled spatial and temporal patterns of snow accumulation and melt, and SMS. The three selected alternative harvesting strategies were: clear-cutting with tree retention, strip-shelterwood, and partial-cut harvesting. The high-level goals of this research were to directly compare and evaluate the effects of the three harvesting strategies on both snowpack accumulation/melt dynamics and explore the lasting legacy of these effects on subsequent growing season SMS. Accordingly, the broad objectives for this thesis were:

1. To quantify and evaluate the comparative effects of each of the three selected harvesting strategies (CC, SS, and PC) on snowpack accumulation and melt; and characterize how each of these harvest strategies affected key environmental factors (radiation and micro-climate) that regulate snowpack dynamics.
2. To evaluate the parallel, comparative effects of each of the three selected harvesting strategies on subsequent growing season SMS dynamics of both shallow soil layers (important in regulating plant water uptake / evaporative losses), and deeper soil layers (important in regulating hillslope and catchment runoff). A companion objective was to explore how these harvesting strategies affected the key radiation and micro-climate variables that regulate seasonal SMS dynamics.

Research of these objectives was divided into two separate phases that are explored in each of the following chapters. Chapter 2 provides a detailed overview of the rationale, materials and methods, results, and discussion of the investigation and findings on the influence of three alternative harvesting methods on spatial and temporal patterns of snowpack accumulation and melt; while Chapter 3 follows the same structure to present findings on coupled spatial and temporal patterns of seasonal soil moisture storage. Finally, Chapter 4 provides a synthesis that outlines the key scientific findings of each preceding chapter, as well as outstanding questions and recommendations for future research.

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Chapter 2: Influence of alternative forest harvesting strategies on spatial and temporal patterns of snowpack accumulation and melt

2.1. Introduction

Melting of snowpack in forested mountain watersheds of the southwestern Alberta Rockies is critical for sustaining stressed regional water supplies (Byrne et al., 2006). However, the quantity and quality of water derived from snowmelt is vulnerable to impacts from both climate change (Stewart, 2009; Clow, 2010), and disturbances including timber harvesting (Moore and Wondzell, 2005; Schelker *et al.*, 2013; Schnorbus and Alila, 2013). Snow accumulation and melt vary highly in space and time based on first-order controls by climate (temperature and precipitation) (DeBeer and Pomeroy, 2017; Lundquist et al., 2013), and secondary control by localized factors including terrain and forest cover at the hillslope to catchment scale (Winkler, 2005; Andréassian, 2004; Dickerson-Lange *et al.*, 2017).

Timber harvesting can affect snow accumulation and melt because forest cover moderates the collective influence of canopy interception, solar energy balance, and wind exposure (e.g., Floyd, 2012; Varhola et al., 2010). Decreases in forest cover typically reduce canopy interception storage, resulting in increased snowpack accumulation in open areas compared to forests (Golding and Swanson, 1986; Hubbart et al., 2015; Schelker et al., 2013). Snowmelt and sublimation losses are strongly regulated by net solar radiation which is influenced by the structure and density of existing forest/vegetation cover. Increasing canopy cover reduces incoming short-wave radiation at the snow surface, but may also increase long-wave radiation due to attenuation and re-emittance by trees (Lawler and Link, 2011; Musselman, 2008; Pomeroy et al., 2009). Additionally, forest cover influences snow accumulation and ablation/melt by modifying patterns of wind redistribution and turbulent heat/water flux (Pomeroy and Granger, 1997), and partitioning of of melt between snowpacks and canopy storage (Storck *et al.*, 2002).

Quantifying the effects of forest cover removal on snow accumulation and melt dynamics is critical to understanding and predicting watershed responses to timber harvesting that may affect local ecology and downstream supply. Numerous studies have been conducted to determine the impacts of timber harvesting on snow accumulation and melt dynamics, predominantly focusing on conventional methods of clear-cutting. Existing literature on clear-cut harvesting show widely varied increases in maximum snow accumulation from five to >100 percent greater than in mature forest stands due to reduced interception (Troendle and Reuss, 1997; Storck *et al.*, 2002; Murray and Buttle, 2003; Gelfan *et al.*, 2004; Winkler *et al.*, 2005; Hubbart *et al.*, 2007; Jost *et al.*, 2007; Boon, 2012; Schelker *et al.*, 2013). However, increased exposure of clearcut snowpacks to solar insolation and turbulent fluxes has also typically been found to result in earlier onset and faster rates of melt (Koivusalo and Kokkonen, 2002; Toews and Gluns, 1986; Winkler et al., 2005). However, while forest disturbance effects on factors controlling increased snowpack accumulation and ablation (losses through melt or sublimation) are generally well understood, the specific effects of differing types of forest disturbance on snowpacks is highly dependent on the complex interaction of vegetative, environmental, and hydrologic factors which govern enhanced snow accumulation and ablation. Where present, coupled increases in snow accumulation and melt rates may negatively effect streamflow regimes due to advances in the magnitude and timing of spring runoff (Winkler et al., 2015). Furthermore, elevated discharge can cause adverse effects due to erosion, flooding, and related damage (Green and Alila, 2012; Harr and Coffin, 1992; Kuras et al., 2012), while earlier runoff may potentially reduce streamflow availability later in the growing season (Clow, 2010; Rood et al., 2008). However, because the interaction of factors regulating snowpack accumulation and losses are not well understood for different types of forest disturbance, potential impacts of forest disturbance on runoff in snow dominated regions remains highly uncertain.

Increased attention is being given to alternative methods of forest harvesting on the basis of reduced potential for adverse hydrologic affects, as well as possible benefits to broader integrated forest-water management objectives. Less extensive research is available for alternative harvesting strategies, but existing studies on strip-shelterwood, and uniform and group selection partial-cutting typically also show increases in snow accumulation corresponding to reductions in canopy cover/interception (Alexander et al., 1985; Gary, 1974; Gary and Watkins, 1985; Hubbart et al., 2015; Leaf, 1975; Troendle and King, 1987; Winkler et al., 2005). However, effects from these strategies on snowmelt differ widely, with separate studies showing both advances and delays in the timing, and duration of snowmelt (Hubbart et al., 2015; Winkler et al., 2005). Highly varied results from existing research on different harvesting strategies show that effects on snowpack accumulation and melt can be broadly attributed to the structure, density, and spatial arrangement of residual trees. However, the comparability of past research is limited by widespread differences among harvesting methods, stand characteristics, and local environmental settings where each study was conducted. Moreover, exceedingly few studies incorporate direct comparisons of multiple harvesting strategies in the same catchment. Comprehensive efforts are needed to further improve our understanding of the effects of specific alternative harvesting strategies on snow accumulation and melt dynamic, results from which are necessary to more accurately predict hydrologic responses to timber harvesting in the context of integrated forest-watershed management and climate change adaptation.

Accordingly, the broad objectives of this research were to evaluate the comparative influence of several alternative harvesting strategies on snow accumulation and melt dynamics, and explore how these different strategies affected the specific environmental factors regulating these critical mountain snowpacks over three consecutive winters. Specific objectives were focused on answering three broad research questions: (1) How do different harvesting strategies impact peak snowpack accumulation?; (2) How do respective harvest cutting patterns influence spatial and temporal patterns of snowmelt?; (3) What are the primary controlling factors affected by harvesting that are responsible for driving observed differences?

2.2. Study area

Research was carried out in the Crowsnest Pass in southwestern Alberta's montane forested front range of the Rocky Mountains. Study sites were located within three sub-catchments (Star West, Star East, and McLaren) of the Star Creek watershed (49° 37' N; 114° 40' W), 7.5 km southwest of the town of Coleman, Alberta, Canada (Figure 2-1). Together with several surrounding watersheds, Star Creek comprises part of a network of catchments that form the Southern Rockies Watershed Project research area, a long-term research project operating since 2004. Star East (389 ha) and Star West (463 ha) sub-catchments form two upper branches of Star Creek and are met by McLaren Creek (95 ha), a seasonally intermittent stream, a short distance below their confluence (Figure 2-1). Star Creek (1855 ha) enters the Crowsnest River forming part of the upper Oldman River watershed. Elevation of the Star Creek watershed ranges from 1475 m to 2631 (Silins et al., 2016), with upslope contributing areas of Star East and West sub-catchments extending into subalpine and alpine zones, whereas the upper sub-alpine portion of McLaren Creek does not does not extend into alpine zones.

Basin mean annual precipitation ranges from 800-1360 mm, approximately 50% of which arrives as snow (Silins et al., 2016; Silins et al., 2009). Snow-melt is a primary contributor to annual discharge in Star Creek. Mean annual temperatures in the region range from –6.4 °C in January to 14.3°C in July (Environment and Climate Change Canada, 2018), however winter air temperatures frequently exceed 0 °C with chinook winds contributing to mid-winter melt periods and rain-on-snow events (Nkemdirim, 1996). Prevailing winds in the Crowsnest Pass are from the west with relatively high wind speeds averaging approximately 18km/hr or more (Alberta Agriculture and Forestry, 2003). Montane forest covers most of the basin at elevations <1900 m with forest cover in both harvested and undisturbed reference sites dominated by lodgepole pine (*Pinus contorta*), alongside lower proportions of white spruce (*Picea galuca*) and Douglas fir (*Pseadotsuga menziesii*). Understory vegetation varies throughout the catchment from moss and shrub dominated ground cover in heavily forested sites, to grass dominated cover in more open areas including forests on south-facing slopes and clearcut sites.

2.3. Materials and methods

2.3.1. Harvest Treatments

Timber harvesting took place in 2015 with separate harvest strategies implemented in each sub-catchment: clear-cut with tree retention (CC) in Star West; strip-shelterwood (SS) in Star East; and a partial-cut (PC) harvest in the McLaren sub-catchment (Figure 2-1; Figure 2-2). CC harvesting consisted of complete stand removal with 15% distributed single-tree and patch-retention within harvested units, over a total area of 69 hectares. Harvesting was divided across south- and north-facing slopes on either side of the Star West drainage, with a 14 ha. northerly aspect unit and a 55 ha. southerly aspect unit. Stand structure of the unharvested retention forest differed moderately between north/south aspects with north-facing stands consisting of higher density evenly aged mature lodgepole pine compared to lower density south-facing stands that had longer live crowns and intermittent gaps or openings between 0.5 – 1 tree heights (H) in size. SS harvesting involved removal of approximately 50% of pre-harvest timber consisting of parallel, alternating CC and forested retention or shelterwood strips approximately 35 m (~ 2H) in width, running from east to west. Strip orientation and width were selected based on the prevailing north-facing slope orientation and stand height to maximize the influence of slope aspect and cutting pattern on snow accumulation and solar insolation after Golding and Swanson (1978). Total harvested area for the strip-shelterwood harvest was approximately 43.8 ha. PC harvesting was carried out over an area of approximately 56 hectares with selective logging of approximately 59%

of stems leaving remaining trees either in groups or uniformly distributed. Evaluation of PC harvesting in this study focused exclusively on the uniform-selection harvest units.

2.3.2. Snowpack Accumulation and Melt

Spatial-temporal patterns in snowpack depth and snow water equivalent (SWE) were evaluated using a paired treatment-reference design. Patterns of snowpack accumulation and melt for each harvest type (CC, SS, PC) were compared with adjacent fully-stocked mature forest “reference” stands from the same sub-catchment using fixed linear transects. Unless specified, results in this study will refer to forested reference sites inclusively, on the basis that statistical comparisons use data collected individually in each respective harvest/subcatchment.

Survey transects consisted of a series of permanent snowpack sampling points marked with vertical painted PVC poles at each measurement location. Transects across all harvests/sub-catchments were located over a similar elevation, ranging from 1575 m.a.s.l. to 1675 m.a.s.l. (Table 2-1). Transect length and measurement point density varied among harvest treatments to reflect differences in spatial variation in canopy structure among treatments, described in turn:

1) CC: sampling points were located along eight transects, four on each south- and north-facing slope, with transects distributed between harvested and reference sites on both upper and lower hillslope positions. Each transect consisted of 6-12 sampling points spaced 7-10 metres apart. Several transects (Figure 2-1) incorporated sampling points that included harvest:forest transition zones however data from these points were excluded from the final analysis in order to avoid confounding influence from “edge” effects.
2) SS: seasonal and spatial patterns of SWE were captured using two transects, placed approximately 100 meters apart and running perpendicularly downslope. Each consisted of 42 sampling points (84 total) bisecting three harvested strips and three shelterwood strips. Points were spaced approximately five meters apart such seven measurement points were distributed equally from edge-to-edge of each forested and harvested strip that (Figure 2-11; Figure 2-11).
3) PC: 41 sampling points were divided between both the harvest and nearby forested reference, with 21 points in the harvested site and 20 points in the forested site. Sampling points in the reference site were divided evenly between two parallel transects, while those in the harvest area were divided into 4 shorter “transect segments” to avoid a logging haul road and maintain a consistent hillslope aspect.

Snow depth and snow water equivalent (SWE = snowpack depth x density) were measured along all transects every 14-21 days beginning prior to, or near the timing of peak SWE, and continuing through to snow disappearance. Transects in CC and SS harvested sub-catchments were measured in both 2016 and 2017, with transects in PC treatments included only during the winter of 2017. All transects were additionally measured once in 2018 near to timing of peak SWE. SWE was measured using a Standard Federal snow corer, with snow samples collected in sealed plastic bags and weighed outside of the field to enable calculation of pack density. Snow depth was assessed between each marked point using a graduated avalanche probe. Due to time constraints, on several occasions SWE was measured at every other fixed transect point, with additional depth measurements collected in their place. Measurements of snow depth were converted to estimates of SWE using an average of the measured density from adjacent snow core samples as described by Dixon et al. (2014).

Continuous change in snowpack accumulation and melt were measured in the SS and PC harvests in 2017 using trail cameras (Stealthcam™ G42NG) to take daily time-lapse photos of snow-depth at fixed staff gauges. Photos were processed by manually recording daily snow depths from images captured at the same time each day (12:00 MST ± 1 hour). Continuous snow depth was measured in the SS at three positions: one in the centre of the forested strip; and two in a harvested strip, one on the south (shaded) side, and one on the north (sun-exposed) side. In the PC harvest, continuous measurements were taken at two representative locations, one within the harvested area and one in the corresponding forested reference site. To assess spatial variation in rates of snowmelt across the SS harvest, snowmelt lysimeters were installed at the same position as time-lapse gauges as well as in the centre of a harvest-strip. Lysimeters were constructed using a 4' x 4' pan which drained into tipping-bucket gauge that was buried at one corner that was placed at one end of a shallow drainage trench meant to transport meltwater downslope. These data were excluded from the analyses because technical difficulties with freezing of meltwater, and wildlife damage to pendant loggers resulted in insufficient data availability and accuracy.

2.3.3. Climatic variables controlling snowpack dynamics

Precipitation was measured with Jarek tipping-bucket precipitation gauges (Geoscientific Ltd.) fitted with anti-freeze overflow systems at a network of long-term climate stations located throughout the catchment (Figure 2-1). Missing precipitation data (due to data logger/equipment malfunction) for some days were gap-filled using the approach described by Ahrens (2006). Seasonal patterns of air temperature were evaluated from two meteorological stations located at representative elevations within the catchment. Missing data for several dates here were gap-filled using a linear regression approach, given air temperature data between the two stations where closely correlated (R^2=0.99, p<0.001). Differences in seasonal temperature between years were described by calculating mean monthly temperature, number of days were average temperature exceeded 0°C, and cumulative degrees days (sum of daily average temperatures above 0°C). Slope, aspect and elevation at were determined by recording the position of transect points using a handheld GPS, then mapping and extracting respective values from a 1m resolution Light Detection and Ranging (LiDAR) Digital Elevation Model (DEM) of the Star Creek basin (collected in 2011) in ArcGIS (version 10.5, ESRI).

Differences in spatial/temporal patterns of coupled snow accumulation and melt were evaluated in the context of differing solar radiation and microclimate forcing in both SS and PC harvest units. Within the SS harvest, spatial variation in microclimate was assessed during 2017 and 2018 using two meteorological stations, one in the centre of the harvested strip and one in the centre of the uncut strip, measuring wind speed and direction (R.M. Young wind monitor, model 05103), and air temperature and relative humidity (Campbell Scientific HMP50) hourly. Data from meteorological stations were collected using Campbell Scientific CR-1000 data loggers. Identical instrumentation was used to measure microclimate variables in the PC harvest, with meteorological towers located in harvested and reference stands, however data were only collected in 2018. Due to project constraints microclimatic data were not collected locally at CC harvest sites.

To evaluate influences from canopy structure on interception/accumulation and melt, vertical hemispherical photos were taken along snow sampling transects points within treed sites including all reference sites, as well as partial cut, and SS harvests. No photos were collected from either north- or south-facing clear cuts because no overhead canopy was present. Images were collected in the field using a Nikon D90 DSLR camera with Sigma 180° fish-eye lens, mounted on a leveled tripod set at breast height (1.3 meters). Images were captured using optimal settings outlined by Chianucci and Cutini (2012), and canopy openness quantified using Gap Light Analyzer (GLA) (Frazer et al., 1999). During processing with GLA, hemispherical photos were reduced from a 180° to 90° field of view to improve measurement of direct overstory canopy by excluding distant trees.

Influence of CC and SS harvests on spatially variable solar radiation and energy forcing was estimated using a Digital Surface Model (DSM) incorporating catchment topography, and the height and position of post-harvest residual trees. The DSM was developed using Light Detection and Radar (LiDAR) point data of individual tree positions and heights prior to harvest collected by AB. Agriculture and Forestry and removing trees from harvested areas shown in the pre-harvest data (i.e. setting tree heights inside harvested polygons to zero (ground level). "Post-harvest" point data were then converted to raster format with cell dimensions set equal to mean crown width (2.2 meters) estimated using relationships between lodgepole pine height and canopy width after Fish et al. (2006). This produced a digital surface model (DSM) of residual stand canopy and harvested ground surface approximating that present in CC and SS harvested sites including their respective land surface topography (slope, aspect, and elevation). Since harvest polygons did not include the position of single-tree retention trees dispersed through PC area, this approach was restricted to only CC and SS harvests. Using this DSM, potential cumulative incoming radiation was calculated for each transect point for the 30-days preceding each measurement date using standard solar radiation modeling functions available in ArcGIS 10.5. Tools for modelling ground/snow surface solar radiation in GIS cannot currently incorporate transmission of radiation through tree canopies (Bode et al., 2014) creating an opaque canopy surface that likely underestimates ground-level incoming radiation in areas shaded by retained trees because some shortwave radiation transmission through the canopy would not be represented using this approach. However, this analysis does provide a meaningful representation of canopy and topographic shading that would describe the majority of harvest effects on incoming shortwave radiation and their spatial variability among harvest cutting-patterns.

2.3.4. Statistical Analyses

A post-hoc comparative analysis of paired harvest and reference sites was used to test the effect of individual harvesting strategies on snowpack accumulation and melt dynamics. Statistical comparison of snowpack dynamics among harvesting strategies were conducted within individual years due to significant interaction between year and snowpack (SWE) resulting from inter-annual climate variation. Assumptions of normality and homogeneity of variances were assessed using

Shapiro-Wilk's test and Levene's test as well as visual examination of plotted residual QQ-plots. Effects of harvesting strategy on annual peak SWE accumulation were tested using Welch's one-way analysis of variance to control for heteroscedasticity and unbalanced sample sizes. Post-hoc pairwise comparisons of peak SWE between corresponding harvested and reference sites were made using the Games-Howell test, which includes no assumption of equal sample-size and variance (Toothaker, 1993). Data from repeated measurements of SWE did not meet homogeneity of variance/compound symmetry assumptions even after data transformation, thus differences in SWE within harvests and respective reference areas were tested individually for each sampling date/period using one-way analysis of variance (ANOVA). Differences in mean microclimate variables between SS and PC harvests, and corresponding forested sites were also assessed using one-way ANOVA. Strength of relationships between SWE and both incoming solar radiation and canopy closure were assessed using Spearman's Rank Correlation test to avoid the need to meet parametric assumptions of normality and equal variance. Simple linear regression relationships were developed to provide additional insight into the role of canopy closure in determining observed SWE. All data analyses were conducted in R (R Core Group, version 3.4.3, 2017; R-studio, version 1.1442, 2017) using a value $\alpha=0.05$ as the threshold for statistical significance.

2.4. Results

2.4.1. Seasonal precipitation and climate

Winter snowfall differed strongly over the three years of the study. Long-term regional snow course data collected at Gardiner Creek, approximately 25 km south of Star Creek, showed respective April 1 SWE in 2016, 2017, and 2018 at 96%, 129%, and 111% of the 31-year average (Alberta Environment, 2018). Long-term data from Star Creek suggested that snow accumulation patterns did not closely follow those at Gardiner Creek (Dixon et al. 2012; Silins et al. 2009) likely due to differences in elevation and subsequent precipitation and temperature, with Gardiner Creek snow courses found at 1900 m.a.s.l. compared to a mean elevation of ~1620 m.a.s.l. for transects in Star Creek. Longer-term snow course data from Star Creek showed 2016 was a low snowfall year with peak SWE at 65% of the mean for the period of 2009-2018, while 2017 and 2018 were high snowfall years with peak SWE at 159% and 150% respectively, relative to the same period.

Early cold-season precipitation for November and December were substantially higher in 2015/16 than 2016/17 (264 mm vs. 114 mm respectively), while the reverse was true during midand late-winter, with 93 mm of precipitation delivered from February to April of 2016, compared to 361 mm over the same period in 2017 (Figure 2-3). Total cumulative precipitation differed between years, with 392 mm of precipitation received from December 1 to April 30 in 2015/16 compared to 518 mm in 2016/17. Seasonal temperatures also differed substantially between years. Over the same time-frame, mean monthly air temperature was 5.2°C lower in 2016/17 than in 2015/16 (Figure 2-3), with 19 fewer days where daily mean temperature was above 0°C (59 vs 78 days). This corresponded to total cumulative degree days (calculated as the sum of daily mean temperatures above 0°C) of 263 in 2016, versus 182 in 2017 (Table 2-2). Differences in this study highlight the principal influence of inter-annual climate variation on snowpack accumulation and melt observations across sampling years.

2.4.2. Peak Snowpack accumulation

Both the timing of snow accumulation and peak SWE varied strongly between harvested and reference stands from 2016 to 2018 (Table 2-3, Table 2-4, Figure 2-4, Figure 2-5). No significant differences in peak SWE between CC harvested and reference stands were found in 2016 and 2017 but in 2018, SWE was significantly lower in the harvested stands ($p<0.05$) where peak SWE was only 56% ($p<0.001$) of that in the adjacent forest on north-facing slopes, and 61% on south-facing slopes ($p<0.05$) (Table 2-3). However, while both CC harvested and reference stands on north-facing slopes had generally greater snowpack depth and SWE comparted to those on south-facing slopes in both 2017 and 2018, SWE did not differ strongly among opposing north-south-facing CCs, or reference sites. Even in 2018 when aspect appeared to have stronger effects on peak SWE in north-, and south-facing CC and reference sites, these differences were not significant ($p=0.619$ and $p=0.167$, respectively). Peak SWE in the SS harvest was significantly higher than in forested reserves for every year surveyed ($p<0.001$, Table 2-3). However, differences in SWE between harvested- and forested-strips varied substantially among years, with the greatest proportional difference (227% greater SWE compared to forested strips) occurring during low snowpack conditions in 2016, compared to 57% and 28% increases in 2017 and 2018 respectively ($p<0.001$; Figure 2-4; Table 2-3). Peak SWE in the PC harvested sites was 27% and 28 % greater than in reference stands in 2017 and 2018 respectively ($p<0.01$, Table 2-3).

Repeated snow-course surveys during 2016 and 2017 showed that peak snowpack accumulation occurred approximately two weeks earlier in CC and PC sites than in the SS site

(Table 2-4). In 2016, peak SWE in CC harvested sites occurred near the March 8 survey date, while SWE in SS harvested sites continued to increase until March 22. In 2017, SWE on transect in both north and south CCs, the PC, and south-facing references sites both peaked near March 18, while peak SWE in the SS and all north-facing reference sites was delayed until near April 1.

2.4.3. Seasonal Snowpack Dynamics

Repeated measurements of snowpack SWE in 2016 and 2017 showed differing patterns of snowpack accumulation and melt among alternative harvesting strategies. Reduced late season precipitation and warmer than average seasonal temperatures in 2016 were associated with low snowpack accumulation and earlier melting, allowing fewer observation dates than were obtained in 2017. Snow surveys in 2016 showed no significant differences in SWE of CC and reference sites on either north- and south-facing slopes during any date, however snowpack disappearance occurred earliest in CC sites (Figure 2-5). SWE in south-facing CCs in 2017 did not differ significantly from forest stands on initial observation dates but became significantly less over the course of the season ($p=<0.001-0.02$, Table 2-5). Conversely, north-facing CC transect had significantly less SWE on early survey dates ($p=<0.001-0.015$, Table 2-5), but differences diminished with the onset of melting. Melting of snow occurred earliest on south-facing aspects in both years, with advanced timing in the reduction of south-facing snowpacks ahead of those on north-facing slopes evident over several sampling periods (Figure 2-5). Subsequent snow disappearance occurred earliest in the south-facing CC, with snowpack disappearance in north/south forest stands and the north-facing CC occurring at similar times (Table 2-4; Figure 2-5). Concurrent snowpack measurements in the SS harvest in both 2016 and 2017 showed significantly higher SWE in harvested-strips than in forested strips across every sampling occasion from prior to peak until disappearance ($p<0.001$, Table 2-5; Figure 2-5). SWE in PC harvested transects was significantly higher than in corresponding forested reference sites on all sampling occasions except the final May 6, 2017/sampling period 6 (Table 2-5) when melting had reduced snowpacks in both harvested/reference sites to similar levels.

Comparison of 2017 time-lapse records suggest snowpack depth in the PC harvest and forested reference sites were highest in mid-winter following a major snowfall event but diminished over the course of the season with snow depth in PC harvest decreasing earlier and at a faster rate. Snow course surveys showed that despite decreasing depth, SWE continued to increase, suggesting earlier ripening of snowpacks in the PC harvest (Figure 2-6). Consequently, increased peak SWE the PC harvest had little influence on timing of snow disappearance, with PC harvest becoming snow free one-day earlier than the adjacent forested site. A rapid acceleration in snow melt-rate occurred across all sites in the catchment after April 30 (Julian day 120 in Figure 2-6) when air temperatures rose significantly, and sensible heat exchange overtook solar radiation as the primary driver of melt.

Snowpack accumulation and melt across harvested SS and residual forested strips was characterized by a high degree of spatial variation that was evident already at the start of time-lapse monitoring on January 15, 2017 (Figure 2-6). Following onset of spring melt, snowpacks along the northern downslope-edge (sunny side) of harvested strips were reduced at a faster rate than those on the opposite shaded south edge (Figure 2-6; Figure 2-8). Field observations and time-lapse monitoring of SS snowpack showed snowpacks within the harvested strip persisted 20 days longer on the shaded southern-edge than on the opposite sun-exposed side, and 15 days longer than in the centre of the forested strip (Figure 2-6; Figure 2-7). Differences in timing of snowpack melt and disappearance in the SS harvest were reflected by spatial patterns of SWE consistent in both repeat-sampling years (Figure 2-8).

2.4.4. Climatic variables controlling snowpack dynamics

Comparison of average daily microclimatic variables showed no significant differences in mean temperature or relative humidity between SS harvested- and forested- strips (Table 2-6). However, mean daily wind speed (1.0±0.3 m s^{-1} and 0.6 ± 0.2 m s^{-1}, respectively) and maximum daily wind speed (7.2±0.3 m s^{-1} and 3.7 ± 0.1 m s^{-1}, respectively) were significantly higher within the harvested strip ($p<0.05$) suggesting harvested-strips are likely subject to increased snow redistribution and sublimation. Similar differences were observed in the PC harvest, where mean and daily maximum wind speed were significantly higher in the uniformly thinned harvest site than adjacent forested reserves, but air temperature and relative humidity were not (Table 2-6).

Modeled differences in incoming solar radiation between north- and south-facing CCs indicated solar insolation (incident radiation) was significantly higher on south-facing slopes, and that SWE was significantly correlated to modelled 30-day cumulative incoming radiation preceding most survey dates (Table 2-7). Associations (Spearman correlations) between incoming radiation and snowpack conditions were strong at timing of peak SWE ($p<0.05$) in both 2016

(0.89) and 2017 (0.62) but became progressively weaker later in the melt period in both years. In the SS harvest, solar radiation modeling demonstrated shading by forested strips created strong differences in incoming radiation across the width of harvested strips. Cumulative radiant energy over the course of the survey period was estimated to be an order of magnitude greater on sun-exposed edges of harvested-strips than on opposite edges, shaded to the immediate south by forested-strips (Figure 2-9; Figure 2-10). Strength of solar radiation forcing across the width of harvested strips increased over the course of the season with increasing day length and solar angle, which reduced the spatial extent of shading over time (Figure 2-10; Figure 2-11). Analysis of the influence of solar radiation indicated a significant negative correlation between preceding 30-day cumulative incoming radiation and depth of SWE measured across the width of harvested strips on every sampling date in both 2016 and 2017 (Table 2-7; ρ= -0.39 to -0.82; $p<0.05$). While solar radiation was not quantified in the PC, differences in canopy cover between fully stocked reference stands and the uniformly-thinned PC suggest differences in ground/snow surface solar radiation exposure are likely significant.

In CC sites canopy closure was not significantly correlated to SWE in 2017, however in 2016 there was a significant positive correlation between SWE and canopy closure on south-facing sites. In both SS and PC harvests, significant negative correlations were evident between canopy closure and patterns of peak and seasonal SWE ($p<0.01$; $p<0.001$, respectively; Table 2-8). These results were supported by significant linear regression relationships ($p<0.05$) between canopy cover and peak SWE, with canopy closure explaining 18% of variation in peak SWE in the SS, and 49% in the PC.

2.5. Discussion

The results of study showed that all three alternative harvesting strategies significantly influenced snow accumulation and melt dynamics, however the specific effects of each on snowpack accumulation and timing of melt were highly dependent on interactions between harvest cutting-patterns (i.e. the spatial arrangement of retained trees) and physical and environmental factors that collectively regulate solar insolation and turbulent energy and water exchange. While a large number of previous studies have explored the effects of timber harvesting on snowpack accumulation and melt dynamics, exceedingly few include direct side-by-side comparison of multiple harvesting strategies in the same catchment. The broad findings of this study show that while all three harvesting strategies affected both snowpack accumulation and timing of melt, the effects of harvesting differed widely among respective strategies, spanning the full breadth of both large increases or decreases in snowpack accumulation, and significant advance or delay in the timing of snowpack melt and persistence/disappearance of snowpacks.

2.5.1. Peak SWE

Forest harvesting is generally accepted to increase peak snowpack accumulation by reducing snowfall canopy-interception losses (e.g., Stegman, 1996; Storck et al., 2002; Teti, 2003; Varhola et al., 2010), however, changes in snow pack accumulation after harvesting may not be directly proportional to reduced snow interception losses because other factors such as increased radiation, wind scouring, and sublimation can also act to reduce snowpacks concurrently. Thus, the net effect on snowpack accumulation depends on how specific harvesting strategies enhanced post-harvest snowpack gains and losses. Very strong increases in peak SWE were evident in harvested-strips, averaging 62% more snow than in forested-reserves over three winter seasons (2016-2018). This was highly consistent with the upper end of increased peak SWE reported after strip-cut harvesting in Fool Ck. Colorado (39% and 58% increase in SWE in 20 and 120 m wide strip cuts, respectively (Leaf, 1975), and substantially greater than that reported for other harvest strategies in early research (e.g. Alexander et al., 1985; Gary, 1974). A comparatively smaller, but still large 28% increase in mean peak SWE observed in the PC harvested areas over the course of this study is also comparable, but at the upper end of 16-30 % increases in peak SWE reported from previous studies on PC harvesting in lodgepole pine (Alexander et al., 1985; Gary and Watkins, 1985; Troendle and King, 1987). However, this study also showed peak SWE was either statistically unchanged or significantly less in CC harvested sites than in adjacent reference forests where mean peak SWE was 35% and 32% less than that of forested sites on respective north- and south-facing slopes across the three study years (Table 2-2). This finding stands in contrast to the majority of previous studies which report increases in peak SWE of 5% to >100% in CC harvested sites or clearings compared to mature forest (Boon, 2012; Gelfan et al., 2004; Hubbart et al., 2007; Jost et al., 2007; Murray and Buttle, 2003; Schelker et al., 2013; Storck et al., 2002; Troendle and Reuss, 1997; Winkler et al., 2005).

Field observations from snow surveys suggest that unchanged or reduced peak SWE in CCs was likely due to greater snowpack losses due to the increased exposure of CCs to wind and shortwave radiation. Wind speed, solar radiation, air temperature, relative humidity influence snow accumulation by regulating evaporation and erosion/sublimation losses (Bernier and Swanson, 1993; Pomeroy et al., 2002; Varhola et al., 2010). While wind speed in CCs was not measured directly, field observations found CC snowpacks were characterized by persistent wind slab formation and solar crusts. Several studies have shown large clearings in areas with high wind exposure may lose snow due to increased turbulent exchange and snow erosion/sublimation (Pomeroy et al., 2002; Swanson, 1980, in Golding and Swanson, 1986; Troendle and Leaf, 1980). Moreover, exposure of larger clearings to solar radiation and turbulent exchange may enhance melt rates in areas where mid-winter melting is frequent (Bernier and Swanson, 1993; Pomeroy and Granger, 1997). Wind speeds in the Crowsnest Pass are higher than in other parts of Alberta, averaging over 5 m s^{-1} (Alberta Agriculture and Forestry, 2003), sufficient to induce snow particle saltation and redistribution (Li and Pomeroy, 1997). Chinook winds in the Crowsnest Pass also cause frequent episodic mid-winter melting that is likely to further offset reduced interception from tree removal. Lastly, the ground surface of our CC sites was mostly cleared of larger debris from tree-felling and limbing ("slash"), which in some harvesting operations is left to increase surface roughness and improve retention of winter snow cover (Pomeroy *et al.*, 1997). Results from this study highlight the need to consider the influence of these important modifying factors when predicting or generalizing clearcutting on seasonal snowpack accumulation.

In contrast, the more moderate post-harvest effects on microclimate variables in PC harvested and SS harvested-strips such as air temperature, humidity, and wind speed did not appear to produce large snowpack losses such as those observed in CC harvested transects. Differences in air temperature and humidity between harvested and forested locations were not evident in both SS and PC harvests (SS $p=0.075$ and 0.76; and PC $p=0.97$ and 0.10, respectively). Moreover, while wind speeds were significantly higher (both $p<0.001$) these data suggest increased wind exposure in both SS and the PC harvests was insufficient to offset snowpack gains from decreased interception. Previous research by (Woods et al., 2006) found no net increase in peak SWE in uniformly-thinned lodgepole pine due to increased wind exposure and sublimation. Contrasting results with the present study can be explained by differences in aspect since north-facing sites in this study experienced comparatively low solar radiation in contrast to more neutral aspect mediated and correspondingly greater ablation/sublimation losses that would be expected on east and west facing slopes studied by Woods et al. (2006). The importance of interception in influencing PC and SS peak SWE is supported by the significant negative relationship found between canopy closure and SWE ($p<0.001$, $R^2=0.49$; and $p=0.03$, $R^2=0.18$, respectively), indicating the largest increases in SWE occurred where the influence of retained canopy was lowest. SS and PC harvests experienced similar levels of canopy removal (50% and 59% of stems respectively) suggesting reductions in interception and area-averaged SWE should have been similar. However, a weaker correlation with canopy-cover and higher inter-annual variability of peak SWE measured in the SS harvest underscores spatially-explicit differences in how each cutting-patterns likely influenced snowpack accumulation, redistribution, and ablation processes.

Inter-annual differences in seasonal precipitation and temperature had differing effects on peak SWE between harvesting systems. SWE was strongly increased during 2016 characterized by mild temperatures and low snowpacks compared to subsequent years with higher snowfall and colder temperatures. During 2016, the ratio of harvest:forest peak SWE in the SS was 3.27, compared to 1.57 and 1.28 in 2017 and 2018 respectively. Peak SWE in CC transects was more consistent however, with corresponding ratios of 0.61 to 0.88, and 0.56 to 1.18, over all three study years in south- and north-facing CC sites respectively. High inter-annual variability of SWE between harvested and forested-strips was likely driven by differences in the distribution of snowfall events and storm intensity among years with variable total snowfall, as well as interactions between temperature, aspect, and shading by forested-strips. Woods et al. (2006) found snowfall interception losses decreased rapidly at storm intensities (daily snowfall amounts) above 5mm SWE/day. Snowfall during this study was not only below average in 2016, but from November 1 to April 30, 2015/16 there were only 16 days when 5mm or more precipitation was received, compared to 33 days over the same period in 2016/17. Data during low snowpack conditions in 2016 show that warmer temperatures and low snowfall in the latter half of the winter caused early reduction of snowpacks in forests and large clearings, whereas snowpacks in harvested strips were preserved by shading from forested-strips. Shading has been shown to have a greater effect on snowmelt during earlier spring warming, because lower solar angles result in larger differences in net radiation received by shaded versus unshaded areas (Lundquist and Flint, 2006; illustrated conceptually in Figure 2-11). Given the importance of these same controlling factors, this concept can logically be extended to shading also having a greater effect on snowpack ablation during warmer winters with more frequent periods of mid-winter melt such as occurred here in 2016. PC harvest snowpacks were not measured in 2016, but early snow ripening and more rapid melting in 2017 and 2018 suggests PC harvesting is less effective at restricting solar irradiance and would therefore also be less effective at increasing snowpacks under milder temperatures and low snowpack conditions.

2.5.2. Spatial and Temporal Patterns of Snowpack accumulation and melt

Spatial and temporal patterns of snow accumulation and disappearance provide critical information necessary for estimating the magnitude, timing, and duration of catchment-average snow melt (Lundquist and Dettinger, 2005). Results from this study reinforce previous research showing that different spatial patterns of tree retention create corresponding variation in spatial and temporal patterns of snowpack accumulation and melt (Varhola et al. 2012; Woods et al., 2006). Previous research on CC harvest snowpacks describe strong differentiation in snowpack accumulation along the edges of surrounding forest, with less variation occurring in the centre of clearings (Golding and Swanson, 1986). Transects in this study were located mostly away from upwind and north/south forest edges thereby reducing forest-edge effects on wind redistribution/deposition, and solar radiation. As a result, CC snowpacks in this study were characterized by relatively uniform surfaces without significant microtopography (i.e. drifts, ridges, etc.). High coefficient of variation (CV) associated with SWE estimates in CC sites occurred instead due to the proportionally lower SWE amounts and fewer sampling points, with actual variation of CC SWE comparable to, or less than in the PC harvest and substantially less than in the SS (Table 2-4: Figure 2-5). Repeated snow-course surveys in 2016 and 2017 show melting advanced earliest in south-facing CCs during both sampling years, with snow disappearance occurring almost two weeks earlier than in north-facing CCs, and forests on both north- and south-facing slopes. Exact day-of-disappearance was not quantified for CCs, but related research has repeatedly shown snowmelt timing generally advances earlier and more rapidly in open areas over adjacent forests (Burles and Boon, 2011; Koivusalo and Kokkonen, 2002; Toews and Gluns, 1986; Winkler et al., 2005). Differences in timing and duration of snowmelt between CCs on north/south slopes here can be attributed to topography-controlled differences in shortwave irradiance, which are illustrated by results from modeling of cumulative incoming solar radiation (Figure 2-11). South-facing slope aspect and clearcutting each increase shortwave radiation exposure, which together have been shown to significantly increase rates of snowpack ablation over adjacent forests and opposite north-facing slopes (Jost et al., 2007; Murray and Buttle, 2003; Packer, 1971; Pomeroy et al., 2003; Winkler et al., 2005). Lack of larger differences in snowmelt timing between north/south-facing forests in this study are similar to results from Ellis et al. (2011 & 2013), who found intact forest cover caused closer snowmelt synchronization between north- and south-facing slopes by restricting topography-controlled differences in shortwave irradiation.

Patterns of snowpack accumulation/melt in the PC harvest were less defined than in the SS harvest, however field observations showed SWE was noticeably reduced beneath retained trees. This was reflected by the strong relationship found between SWE and canopy closure (Table 2-9; Figure 2-14). Areas surrounding retained trees were first to experience loss of snowpack (Figure 2-7), a pattern consistent with research describing variation in SWE and melt rates due to overhead canopy interception and emitted longwave radiation from tree stems (Faria et al., 2000; Musselman, 2008; Pomeroy et al., 2009). Snow-course surveys and time-lapse images show SWE in PC harvested sites continued to increase despite decreased snow depth (Figure 2-6) yet snow disappearance occurred at approximately the same time as in the adjacent fully-stocked forest stand. This suggests that deeper snowpacks in PC transects experienced earlier snow ripening and increased melt rates, consistent with Winkler et al. (2005) who described earlier onset of snowmelt in thinned stands of juvenile lodgepole pine. While solar radiation was not modeled for the PC, earlier melting is likely because the open distribution of retained trees provided limited shading from incoming shortwave radiation. Moreover, net radiation may actually increase due to attenuation of this energy by spatially-dispersed sunlit trunks, as noted by past research (Woo and Giesbrecht, 2000). Additional research characterizing sub-canopy radiation dynamics in PC systems is needed to better quantify these processes.

Field data and observations in this study show that snowpack dynamics after SS harvesting were consistent with the hypothesis that radiation forcing from shading by forested-strips would create distinct spatial and temporal differences in snow accumulation and melt. SWE was increased on south-edges shaded by retained trees but reduced on opposite sunlit north-edges. Time-lapse images of snow depth show that these spatial patterns developed early in the winter prior to commencement of time-lapse monitoring and increased over the course of the season (Figure 2-6). Timing of snow disappearance in 2017 (Figure 2-6, and Figure 2-11) corresponded to differences in SWE/depth, with snowpacks on the shaded south-edge of harvested-strips persisting 20 days longer than on opposite sunlit-edges, and 15 days longer than in the centre of forested-strips. Spatial and temporal patterns of snowpack accumulation in SS transects (Figure 2-

8) in this study were similar to those observed in early research on SS harvests (Alexander et al., 1985), including Halverson and Smith (1974) and Anderson (1956) who both noted increased short-wave radiation and long-wave back-radiation from tree stems on the sunlit-edges of similarly east-west oriented strips.

The key role of solar radiation in driving spatial and temporal patterns of snow accumulation and melt in this study is evident from strong relationships between SWE and modeled incoming radiation (Table 2-6; Figure 2-10; Figure 2-11). Radiation forcing in our strip-shelterwood harvest was maximized by interactions between strip-orientation and width, slope-aspect, and solar angle (shown conceptually in Figure 2-11) with northerly aspect, E-W strip-orientation, and strip-widths of approximately 2H enhancing the extent and duration of shading experienced by harvested-strips. These results directly demonstrate strip-harvest radiation dynamics modeled by Harrington (1984), as well as relate indirectly to more numerous studies on snowpack dynamics in small clearings/clearcuts which show analogous accumulation and melt patterns as a result of the same processes (Golding and Swanson, 1986; Penn et al., 2012; Stegman, 1996; Troendle and Reuss, 1997; Veatch et al., 2009; Woods et al., 2006). Golding and Swanson (1978) found less than 40% of the snow surface in clearings 2H in size was subject to direct solar radiation at the onset of spring melting on April 8 at James River, AB (latitude 52°N). Research by Ellis et al. (2013) found small clearings increased the magnitude, and duration of catchment snowmelt, by increasing snow accumulation, and by simultaneously causing earlier melting on south-facing slopes and slower melting on north-facing slopes. While SS harvesting in this study was not carried out on south-facing slopes, given the same controlling factors results would likely compare similarly with those described for harvested gaps. Studies on snowmelt dynamics have shown shading in small openings by surrounding trees creates “cold-holes”, where snowmelt is delayed because higher SWE and reduced net radiation result in a greater accumulated energy deficit (cold-content) than surrounding snowpacks (Bernier and Swanson, 1993; Ellis et al., 2013). Results here demonstrate that E-W oriented SS harvesting on north-facing slopes leverage the same processes to create “cold-edges”, which enhance topography-controlled shading to similarly increase snow accumulation and melt duration.

2.6. Conclusions

1. All three harvesting strategies significantly affected snow accumulation and melt dynamics, however effects differed widely between methods. Differing spatial and temporal patterns of snowpack accumulation and melt among alternative harvesting strategies occurred because spatial patterns of tree retention produced both differing spatial patterns of canopy interception that controlled snow accumulation, and solar insolation and wind exposure that controlled snowpack ablation (losses).
    a. CC harvesting resulted in either unchanged or significantly reduced snowpack accumulation because reduced interception losses were offset by similar or greater loss from increased wind and solar radiation exposure. This finding is in contrast with previous research that typically report increases in peak SWE highlighting the importance of local conditions in regulating both snow accumulation and ablation dynamics.
    b. SS harvesting had the greatest effect on increasing peak SWE by 62% in harvested-strips and extending snowmelt duration by more than two weeks, because of reduced interception and strong solar radiation forcing because of shading by forested-strips.
    c. PC harvesting resulted in significantly increased in snow accumulation because of reductions in canopy interception. However, snowmelt was faster and occurred in synchronization with forest snowmelt due to decreased shading offered by spatially-dispersed residual trees.
2. Slope aspect was a critical factor in influencing the effect of different harvesting strategies on snow accumulation and melt timing. For example, radiation forcing in the SS harvest was maximized by the interaction of topographic shading provided by northerly hillslope aspect with shading by forested retention strip. Findings here strongly reinforce the importance of radiation as moderator of snow accumulation and melt, and demonstrate the need to consider slope orientation and patterns of tree retention as key factors regulating the rate, timing, and synchronization of catchment snowmelt.

Past research has widely described changes in volume and timing of runoff generation as a result of forest harvesting effects on snow accumulation and melt (Brown et al., 2005; Stednick, 1996; Winkler et al., 2015). The differing spatial and temporal patterns of snowpack accumulation and ablation observed herein are likely important drivers of the differential effects of these harvest strategies on catchment runoff dynamics. Detailed assessment of corresponding impacts on timing of streamflow generation, peak flows, and annual discharge will provide valuable information needed to evaluate the potential of alternative strategies for improving regional integrated forest-water management strategies.

Table 2-1: Summary of mean elevation, slope, aspect, and canopy closure among harvested and references sites; ± values are standard deviation.

Harvesting Strategy	Mean Elevation (m.a.s.l.)	Slope Range (deg)	Aspect	Canopy closure (%)
Clearcut N	1598 ± 22	8-18	N	0
Clearcut S	1607 ± 28	0-14	SE	0
Reference N	1644 ± 1	23-24	N	56 ± 15
Reference S	1594 ± 5	8-16	SE	46 ± 26
Strip-cut	1652 ± 14	6-17	NNE	9 ± 11
Strip-forest	1647 ± 11	8-16	NNE	51 ± 8
Partial-cut	1603 ± 15	12-18	N	27 ± 17
Partial-cut Reference	1580 ± 4	3-12	N	57 ± 5

Table 2-2: Summary of cold-season temperature and precipitation: November 1 to April 30, 2015/16 and 2016/17, described by number of days with mean temperature >0°C, and cumulative degree days (measured as the sum of mean daily temperatures >0°C), and total precipitation over the period.

Season	Days above 0°C	Cumulative Degree Days	Total precipitation (mm)
Nov 1. 2015 to Apr. 30, 2016	78	263	392
Nov 1. 2016 to Apr. 30, 2017	59	182	518

Table 2-3: Peak SWE (mm) and ratio of peak SWE between harvested:reference sites (shown in parentheses) in 2016, 2017, and 2018. Mean ratio of peak SWE (harvested:references sites) across 2016-2018 is shown at right with significant differences (p<0.05) denoted by bold text.

Harvesting Strategy	2016	2017	2018	Mean (2016-2018) peak SWE ratio
Clearcut (South)	14.8 (0.88)	121.4 (0.68)	126.7 (0.61)	0.72
Clearcut (North)	34.7 (1.18)	149.6 (0.76)	159.8 (0.56)	0.83
Strip-shelterwood	187.9 (3.27)	325.2 (1.57)	332.1 (1.28)	**1.43**
Partial Cut	NA (NA)	230.7 (1.28)	259.9 (1.27)	**1.28**

Table 2-4: Summary of SWE (mm) measurements from 2016 and 2017 snow course surveys. Numbers in parentheses are values for corresponding forested reference transects on the same sampling date. Shaded columns indicate approximate timing of peak SWE accumulation in each respective year.

2016

	8-Mar			22-Mar			5-Apr			19-Apr		
Harvest	Clearcut N	Clearcut S	Stripcut	Clearcut N	Clearcut S	Stripcut	Clearcut N	Clearcut S	Stripcut	Clearcut N	Clearcut S	Stripcut
Mean SWE	34.7 (29.4)	14.8 (16.9)	167.8 (66.0)	30.2 (23.4)	6.3 (22.3)	187.9 (57.4)	0 (4.7)	0 (3.8)	155.8 (27.0)	0 (0)	0 (0)	56.9 (0)
StdDev	25.5 (31.7)	29.6 (29.4)	85.4 (36.1)	27.1 (27.1)	15.5 (37.8)	109.1 (43.0)	0 (11.0)	0 (12.2)	106.2 (36.5)	0 (0)	0 (0)	91.7 (0)
CV	0.74 (1.07)	1.99 (1.73)	0.51 (0.55)	0.90 (1.16)	2.45(1.69)	0.58 (0.75)	0 (2.32)	0 (3.2)	0.68(1.35)	0 (0)	0 (0)	1.61 (0)
Max	67 (89)	74 (97)	443 (167)	98 (92)	38 (142)	527 (189)	0 (33)	0 (47)	470 (135)	0 (0)	0 (0)	342 (0)
Min	0 (0)	0 (0)	39 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
n	11 (28)	6 (28)	83 (83)	22 (28)	6 (28)	83 (83)	11 (11)	17 (27)	83 (83)	22 (28)	28 (28)	83 (83)

2017

	20-Feb				4-Mar				18-Mar			
Harvest	Clearcut N	Clearcut S	Stripcut	Partialcut	Clearcut N	Clearcut S	Stripcut	Partialcut	Clearcut N	Clearcut S	Stripcut	Partialcut
Mean SWE	93.8 (157.6)	119.1 (138.1)	213.0 (167.3)	165.8 (158.5)	123.6 (184.9)	109.4 (144.8)	229.5 (174.3)	199.2 (164.2)	149.6 (195.8)	121.4 (177.4)	294.0 (205.8)	231.0 (181.2)
StdDev	31.0 (55.3)	35.4 (83.3)	82.2 (38.5)	62.2 (33.2)	50.7 (44.4)	46.1 (65.7)	64.9 (34.1)	37.5 (18.9)	66.3 (61.3)	54.2 (80.5)	92.8 (39.1)	55.3 (28.3)
CV	0.33 (0.35)	0.30 (0.60)	0.39 (0.23)	0.24 (0.15)	0.41 (0.24)	0.42 (0.44)	0.30 (0.20)	0.19 (0.12)	0.44 (0.31)	0.45 (0.45)	0.32 (0.19)	0.24 (0.16)
Max	157 (253)	182 (431)	562 (268)	265 (184)	233 (270)	267 (257)	429 (280)	277 (210)	273 (309)	251 (337)	510 (311)	314 (256)
Min	44 (75)	59(0)	114 (93)	103 (109)	48 (110)	32 (18)	121 (103)	106 (122)	54 (88)	22 (14)	140 (124)	105 (121)
n	22 (28)	17 (28)	83 (83)	38 (38)	22 (28)	32 (28)	83 (83)	38 (38)	22 (28)	31 (29)	83 (83)	38 (38)

	Apr. 1				14-Apr				6-May			
Harvest	Clearcut N	Clearcut S	Stripcut	Partialcut	Clearcut N	Clearcut S	Stripcut	Partialcut	Clearcut N	Clearcut S	Stripcut	Partialcut
Mean SWE	136.9 (197.1)	57.6 (114.3)	325.2 (207.6)	230.7 (180.7)	127.7 (152.9)	17.4 (71.9)	314.6 (180.0)	225.8 (164.3)	0 (0.9)	0 (0)	180.0 (69.8)	66.9 (50.5)
StdDev	66.5 (63.8)	54.2 (82.1)	125.9 (58.5)	59.8 (31.1)	69.5 (60.5)	34.9 (74.5)	132.9 (65.7)	73.5 (29.7)	0 (2.4)	0 (0)	169.5 (75.3)	69.6 (29.0)
CV	0.49 (0.32)	0.94 (0.72)	0.39 (0.28)	0.26 (0.17)	0.54 (0.40)	2.0 (1.0)	0.42 (0.36)	0.33 (0.18)	0 (0.259)	0 (0)	0.94 (1.08)	1.04 (0.57)
Max	266 (342)	196 (262)	729 (375)	337 (244)	292 (259)	126 (271)	653 (334)	329 (259)	0 (9)	0 (0)	550 (238)	231 (96)
Min	65 (85)	0 (0)	123 (95)	56 (114)	38 (29)	0 (0)	82 (48)	22 (99)	0 (0)	0 (0)	0 (0)	0 (0)
n	22 (28)	31 (29)	83 (83)	38 (38)	22 (28)	31 (29)	83 (83)	38 (38)	22 (28)	31 (29)	83 (83)	38 (38)

Table 2-5: Summary of statistical comparisons between SWE (mm) of harvested and forested reference sites for repeated snow course surveys through 2016 and 2017. Sampling period numbers correspond chronologically to survey dates for each year described in Table 4. Bolded text indicates significant differences at α=0.05.

		p-values					
Year	Sampling Period:	1	2	3	4	5	6
2016	Clearcut N	0.59	0.38	**	N/A	–	–
	Clearcut S	0.87	0.11	**	N/A	–	–
	Strip-cut	**<0.001**	**<0.001**	**<0.001**	*	–	–
2017	Clearcut N	**<0.001**	**<0.001**	**0.015**	**0.002**	0.19	**
	Clearcut S	0.29	**0.02**	**0.002**	**0.003**	**<0.001**	N/A
	Partial-cut	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	0.18
	Strip-cut	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**

*No snow remaining in forested site

**No snow remaining in harvested site

N/A - no snow present in both harvest and reference site

Table2-6: Comparison of mean climatic variables ± std. deviation within the middle of a harvested and forested strip, Jan 1-May 5, 2017; and partial-cut harvest and forested reference (March 3-May 13, 2018). Bold text denotes significant differences ($p<0.05$).

	Air Temperature (deg C)	Relative Humidity (%)	Mean Daily Wind Speed (m/s)	Mean Maximum Wind Speed (m/s)
Strip Cut	-4.8 ± 0.7	75.1 ± 1.4	**1 ± 0.1**	**7.2 ± 0.3**
Strip Ref	-4.7 ± 0.7	74.9 ± 1.4	0.6 ± 0.0	3.7 ± 0.1
Partial-cut	0.3 ± 6.1	70.2 ± 17.2	**1.0 ± 0.4**	**4.8 ± 1.6**
Partial-cut Reference	0.3 ± 5.6	74.7 ± 14.6	0.5 ± 0.2	1.0 ± 0.3

Table 2-7: Spearman's Rank Correlations between harvested-strip SWE (mm) and 30-day cumulative radiation (W m^{-2}) in 2016 and 2017. Asterisks denote level of statistical significance (*p<0.05; **p<0.0001). NA denotes periods where transects were devoid of snow.

Location	Year	Sampling Period 1	2	3	4	5	6	Overall
SS	2016	-0.59**	-0.67**	-0.76**	-0.73**	–	–	-0.68**
	2017	-0.39*	-0.65**	-0.76**	-0.77**	-0.82**	-0.63**	-0.08
CC	2016	-0.89*	0.28	NA	NA	–	–	-0.77**
	2017	-0.73*	-0.71*	-0.62*	0.35	0.54	NA	-0.08

*p=<0.05
**p<0.001

Table 2-8: Spearman's Rank Correlation testing of the relationship between percent canopy closure and SWE (mm) at peak and throughout the season (overall). Spearman's rho values are provided adjacent to significant results based on α=0.05.

Year	Harvest	Peak SWE	Overall
2016	Clearcut N	p=0.4	p=0.58
	Clearcut S	p=0.01, -0.63	p=0.007, -0.35
	Strip-shelterwood	p<0.001, -0.77	p<0.001, -0.48
2017	Clearcut N	p=0.58	p=0.09
	Clearcut S	p=0.39	p=0.08
	Strip-shelterwood	P=0.006, -0.56	p=0.001, -0.28
	Partialcut	p<0.001, -0.70	p<0.001, -0.47

Figure 2-1: (A) Location of the study area in Star Creek watershed, in relation to the community of Coleman, Alberta. (B) Schematic map of harvesting treatments in the Star Creek catch, including locations of snow course sampling transects and meteorological stations.

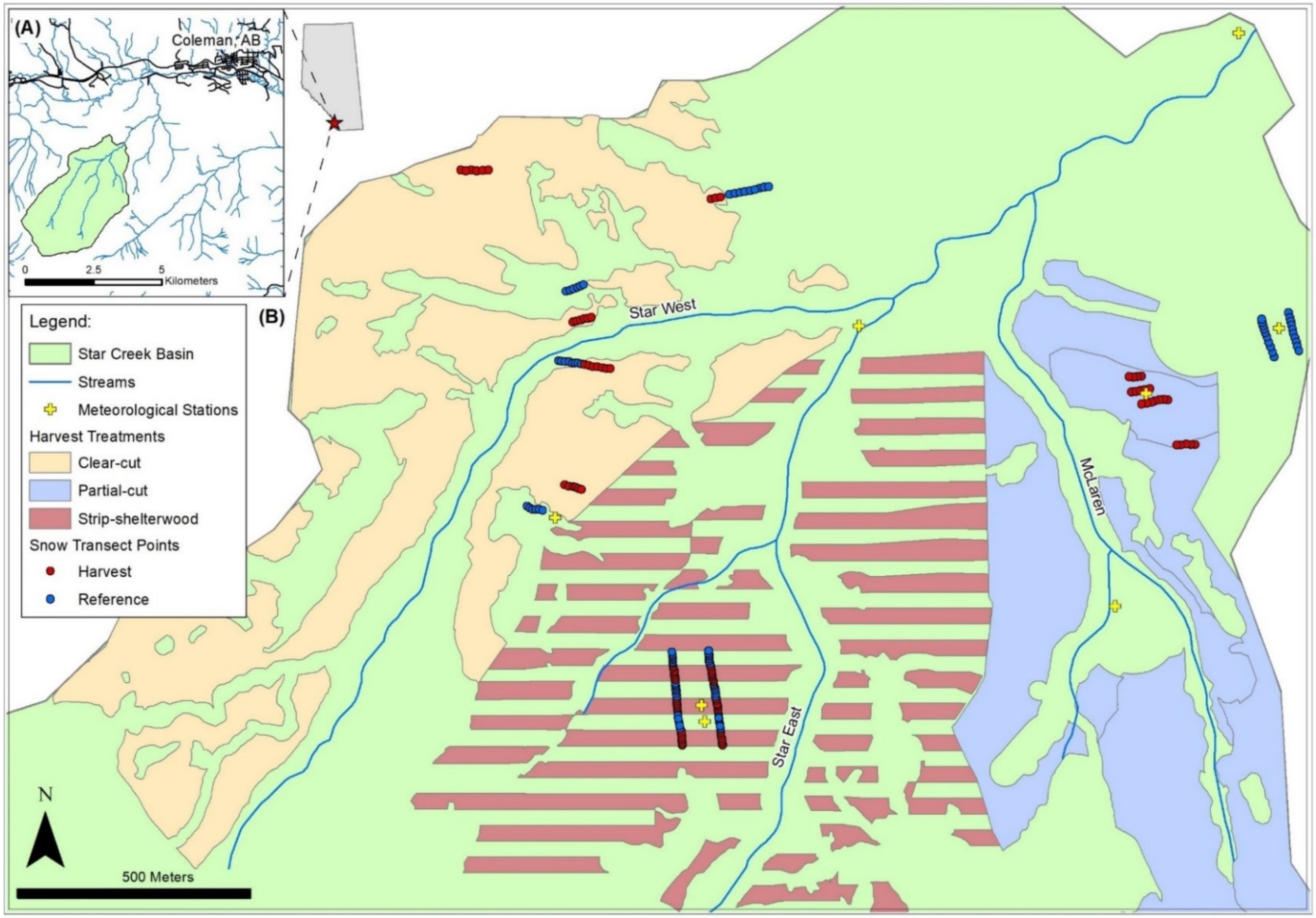


Figure 2-2: (A) Orthorectified satellite image of the harvest area in Star Creek; (B) LiDAR derived digital elevation model of the harvest area, where lighter colours denotes higher elevation; (C) Map of harvest area slope distributions; (D) Distribution of hillslope aspects across the harvest area.

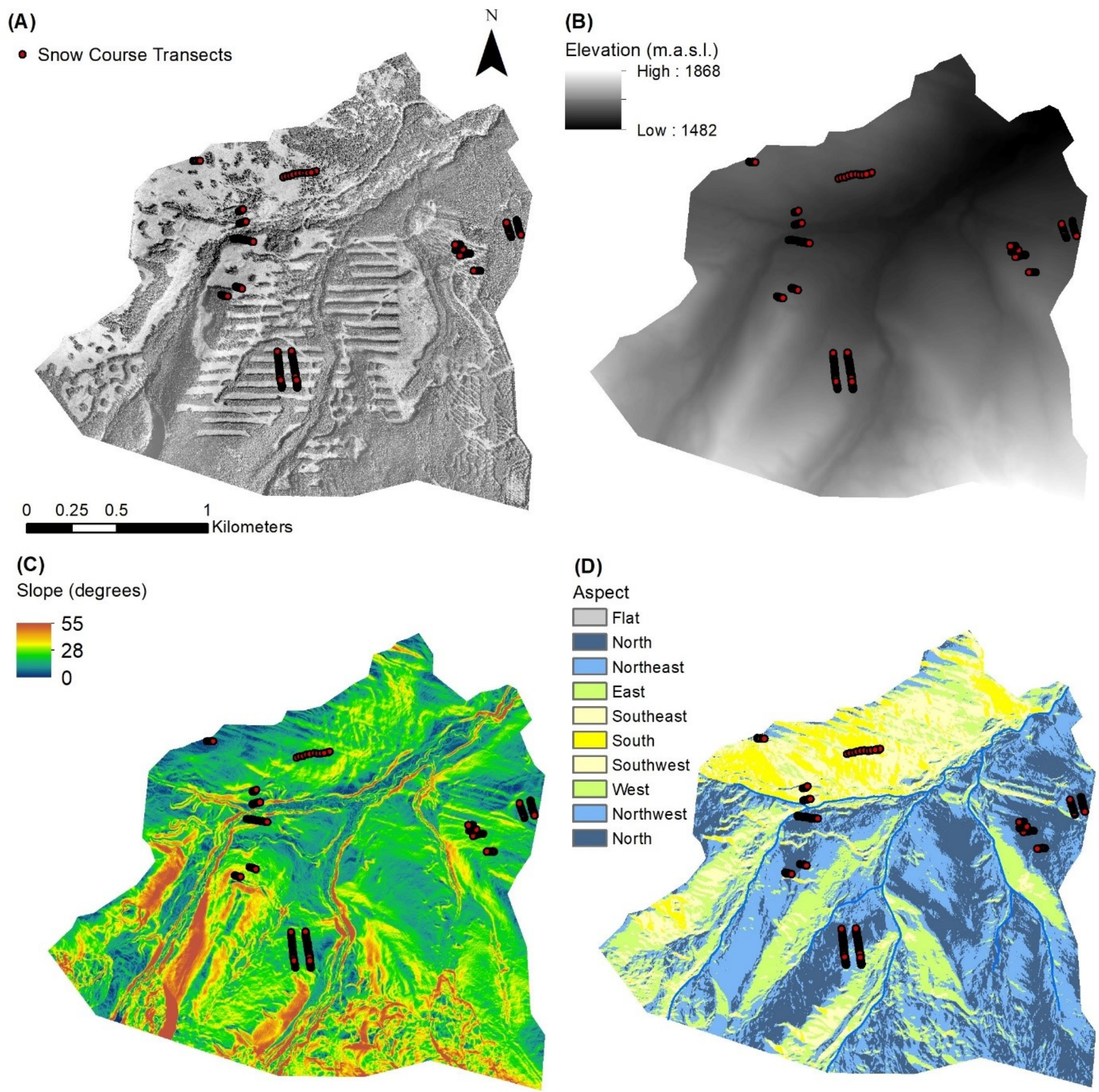


Figure 2-3: Total monthly precipitation and mean monthly temperature for November 1 to April 30, 2015-2016 and 2016-2017 respectively. Dotted line denotes freezing point (0°C).

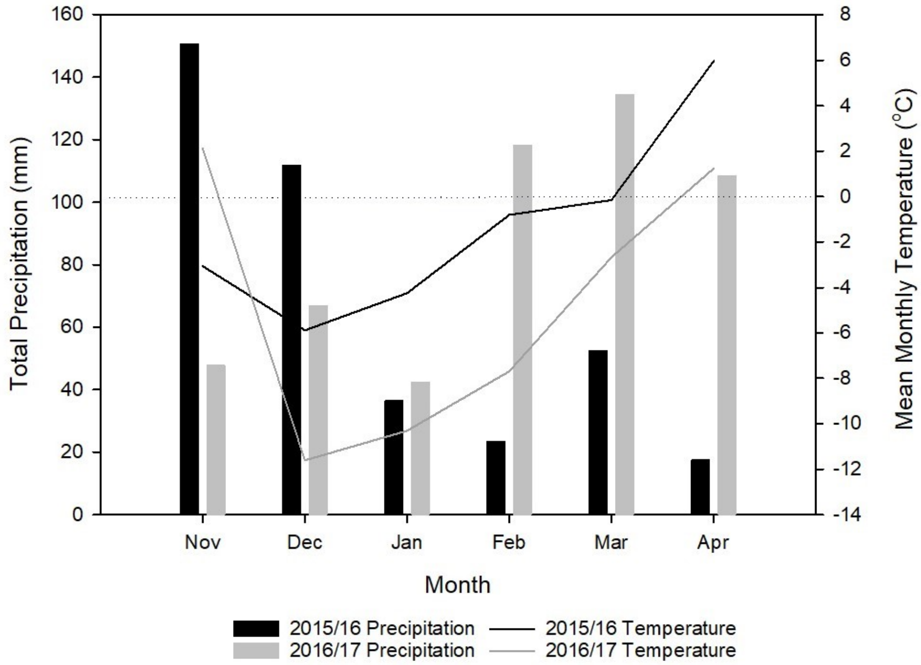


Figure 2-4: Box-whisker plots of peak SWE for 2016, 2017 and 2018 peak SWE, for paired harvested and reference transects as follows; "CC-S" = South facing Clearcut, "CC-N" = North facing Clearcut, "SS" = Strip-shelterwood, "PC" = Partial-cut". Upper and lower rectangle bounds denote 25th and 75th percentiles where horizontal lines indicates the median, X indicates samples means, "whiskers" denote 10th and 90th percentiles, and solid dots indicate outliers . Partial-cut and corresponding reference sites (PC) were surveyed only in 2017 and 2018.

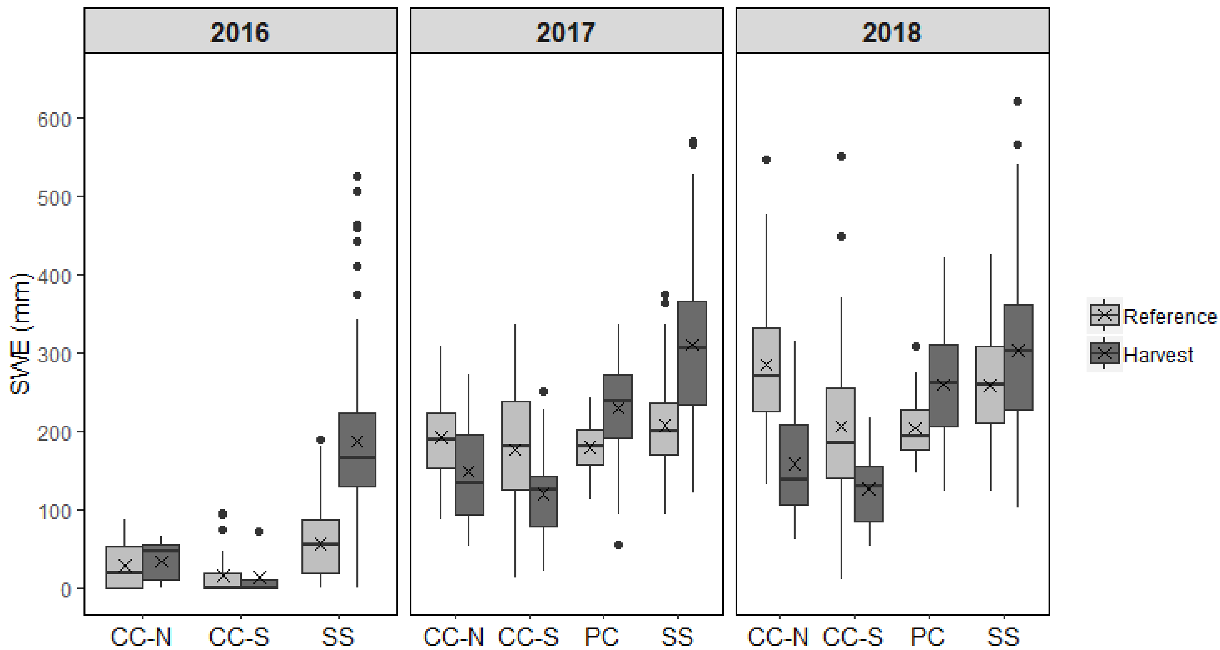


Figure 2-5: Box-whisker plots of SWE from repeated measurements in 2016 and 2017. Upper and lower rectangle bounds denote 25th and 75th where the horizontal line indicates the median, X indicates samples means, "whiskers" denote 10^{th} and 90^{th} percentiles. Harvest site data are described by dark grey plots and corresponding reference sites by lighter grey

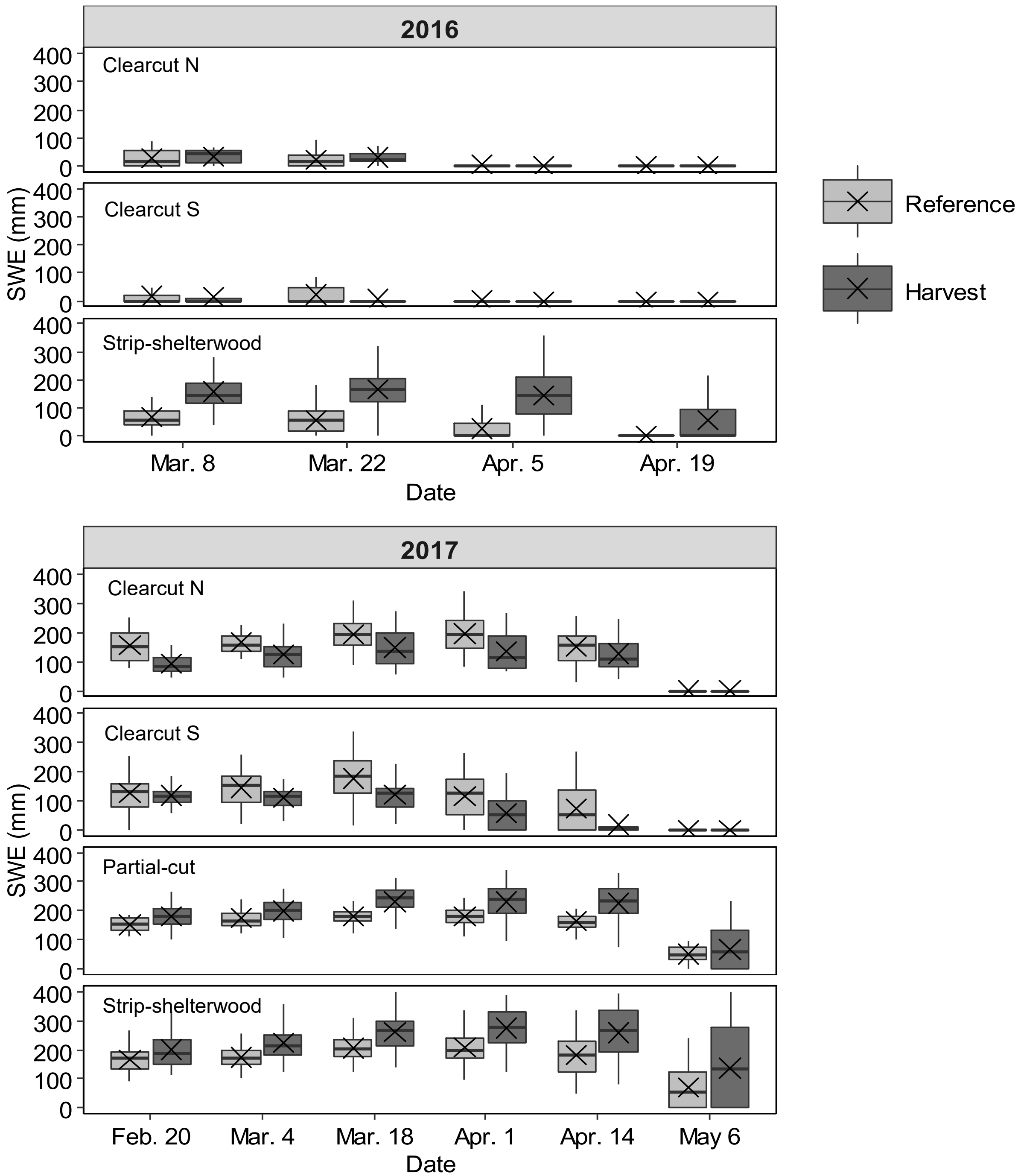


Figure 2-6: Comparison of seasonal snow depth evolution in partial-cut, strip-shelterwood, and forested reference points harvested sites captured at daily time-step using time-lapse images. North and South lines within the strip-shelterwood harvest describe spatial-temporal patterns of snowpack depth on opposing sun-exposed (North) and shaded (South) sides of a harvested strip. Point data show SWE measured on corresponding dates at each location.

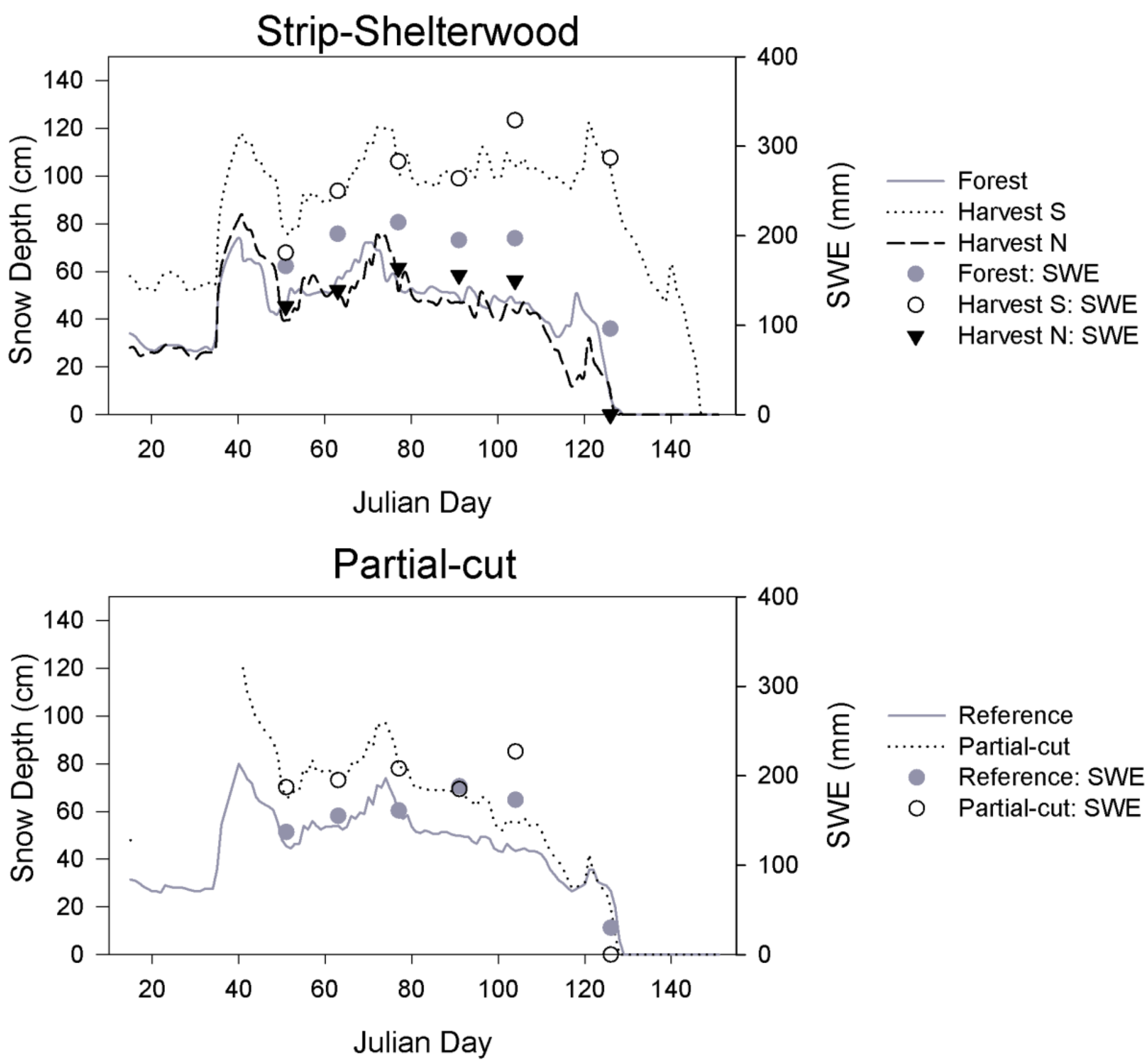


Figure 2-7: Comparison of snowpacks between differing harvest types in mid-winter (Feb. 18 and March 4-5, 2017) and during the spring melt period (May 4-5, 2017)

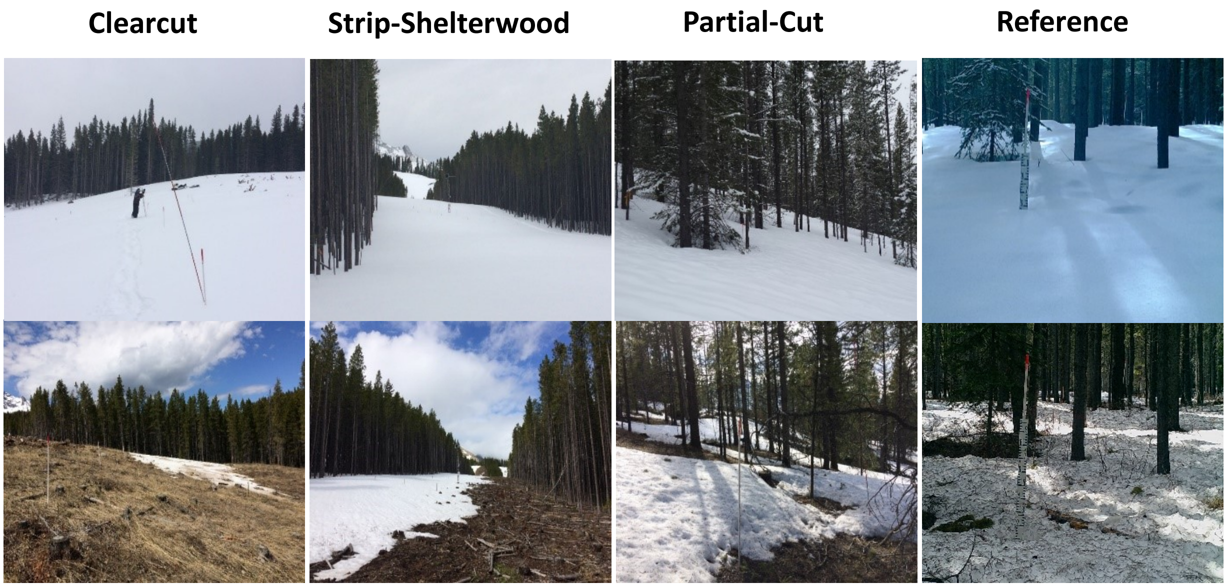


Figure 2-8: Spatial distribution of average SWE (mm) at each sampling position across the width of harvested and forested strips for three sampling occasions in 2016 and 2017. Vertical dashed line indicates transitions point between harvested and forested/shelterwood strips.

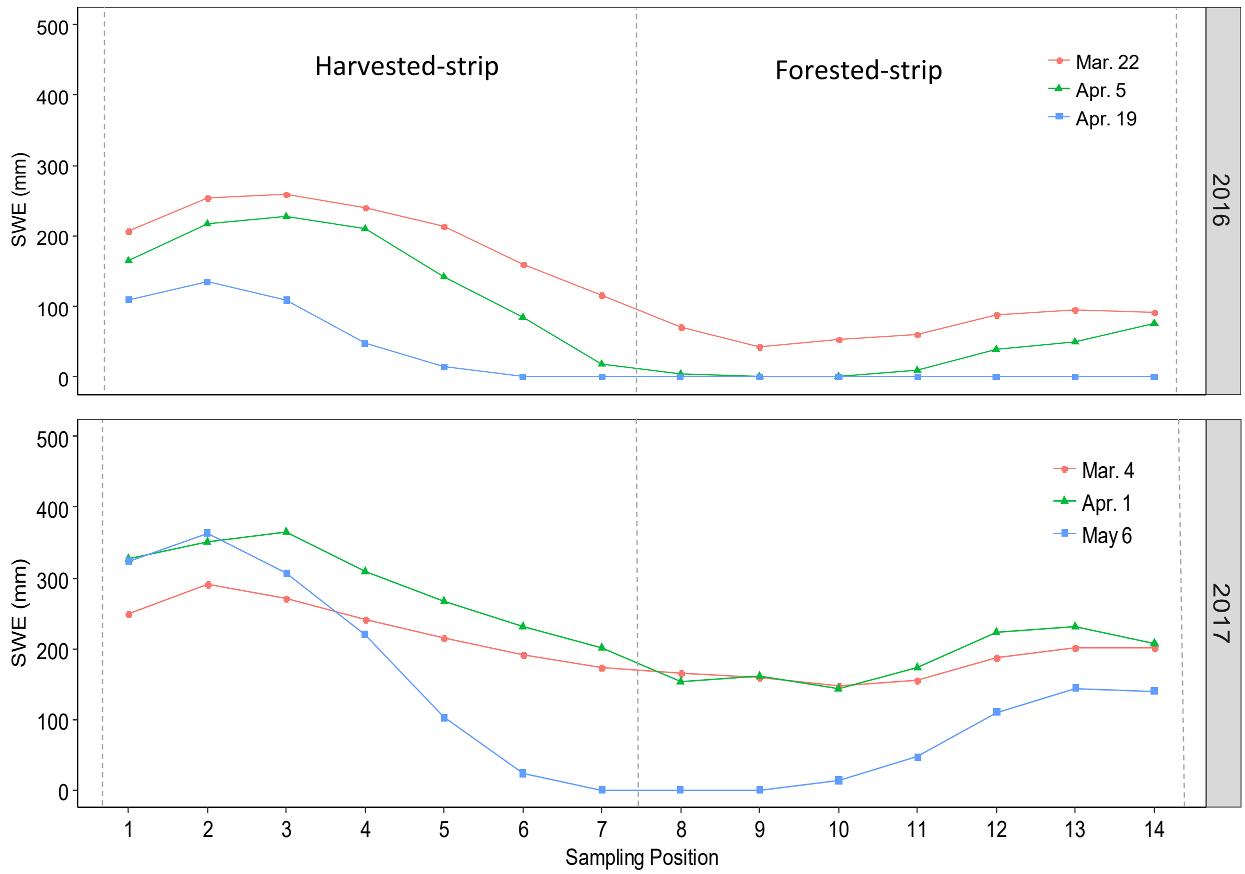


Figure 2-9: Comparison of spatial variation in 30-day cumulative incoming radiation (W m^{-2}) across the width of a harvested-strip for three SWE sampling dates in 2017. Numbered x-axis denotes relative position of uniformly spaced SWE sampling points.

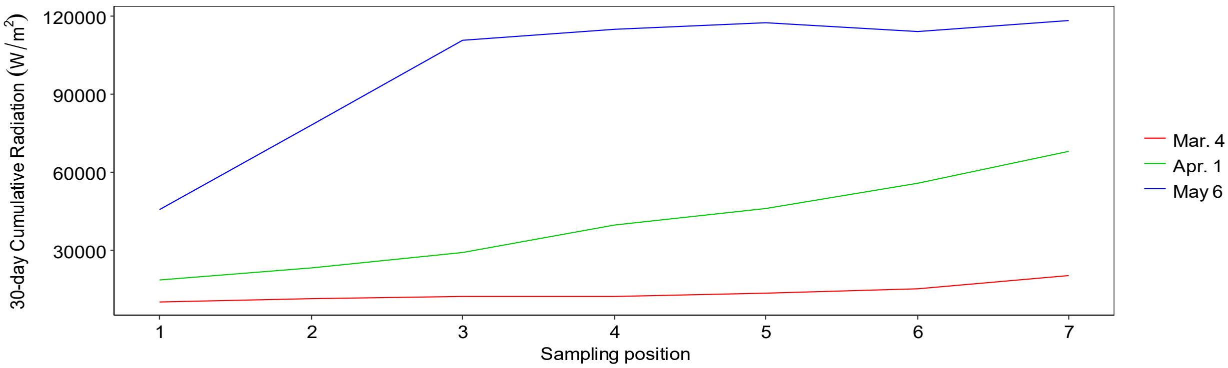


Figure 2-10: Harvest modeled total cumulative incoming radiation received over the duration of 2017 snow-course surveys in north and south clearcut (left image), and strip-shelterwood (right image) harvests. Warm colours denote higher incoming radiation, while cold colours denote lower received radiation.

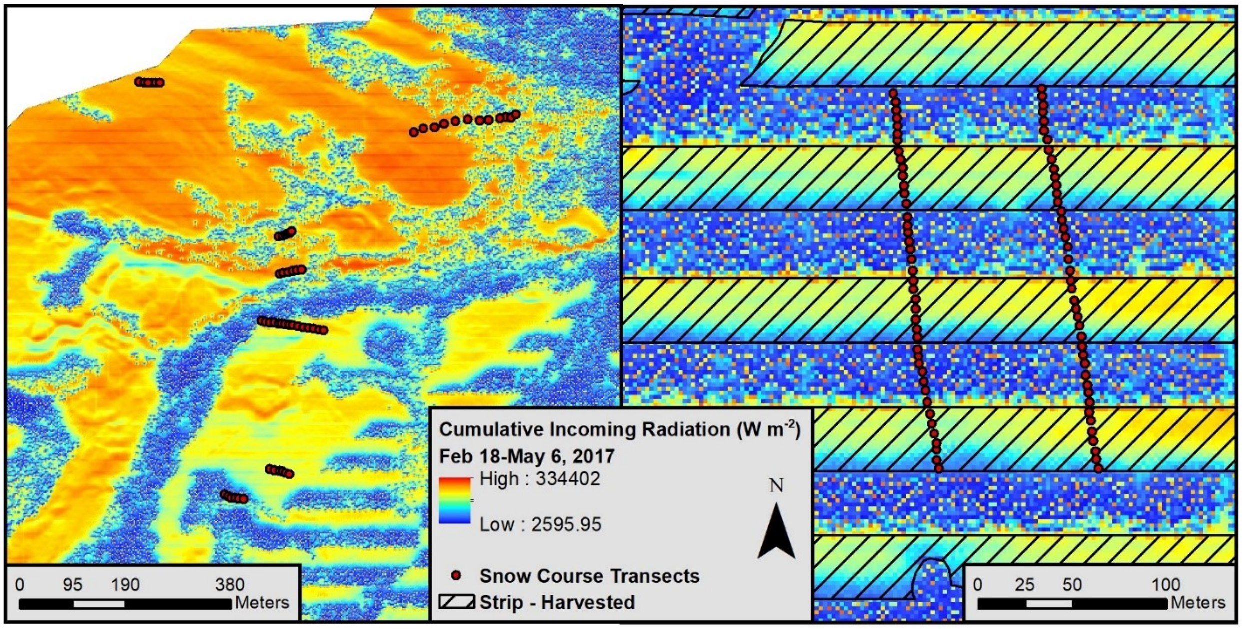
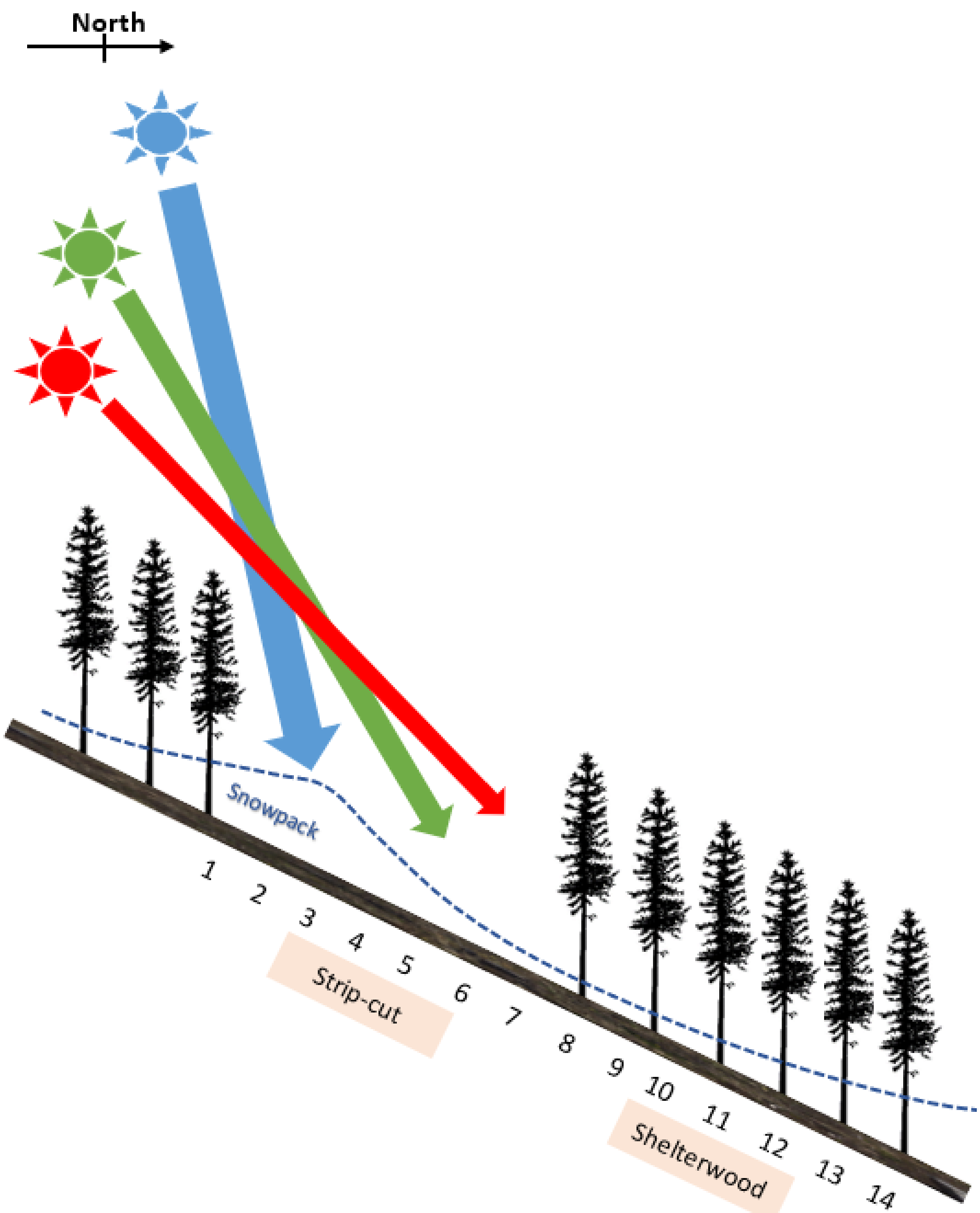


Figure 2-11: Conceptual diagram of spatial-patterns of snowpack accumulation and melt within the strip-shelterwood harvest. Sun xenith position, and arrow angle and size illustrate seasonal increase in spatially-coupled incoming solar radiation. Number positions (1-14) correspond to relative positions at which SWE was measured across the width of harvested and forested strips.



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Chapter 3: Influence of alternative forest harvesting strategies on spatial and temporal patterns of seasonal soil moisture storage

3.1. Introduction

Soil moisture links fundamental hydrologic processes that control water and energy exchange between the land surface and atmosphere, including precipitation infiltration, evaporation, transpiration, groundwater recharge, and runoff (Rodriguez-Iturbe et al. 1999; Koster et al. 2004). Soil moisture is the predominant factor that determines the distribution and function of ecological communities, however it also serves a vital function in moderating runoff that sustains streamflow from forested headwaters. Spatial and temporal patterns of soil moisture storage (SMS) are broadly controlled over time by seasonal and interannual meteorological conditions at larger scales, and spatially by more static factors including topography, soils, and vegetation cover (Tueling and Troch, 2005). In snow-dominated watersheds knowledge of spatial and temporal patterns of antecedent soil moisture have been shown to significantly improve the accuracy of streamflow forecasting (Harpold et al., 2017) because SMS determines threshold levels of snowmelt and rainfall necessary to generate runoff (Buttle et al., 2005; Laudon et al., 2004; Merz and Plate, 1997; Penna et al., 2011; Seyfried et al., 2009; Tromp-van Meerveld and McDonnell, 2006). However, SMS controls on runoff from forested mountain headwaters are susceptible to land disturbances such as timber harvesting, that alter hydrologic processes which regulate soil-water balance.

Timber harvesting impacts spatial and temporal soil moisture dynamics because loss of forest covers alters processes that control soil-water balance, including precipitation interception, transpiration, solar energy balance, and turbulent vapour exchange (Korres et al., 2015; Stednick, 1996; Wilson et al., 2004). Removal of forest cover have been shown to typically increase seasonal soil moisture by reducing interception and transpiration by trees (Bosch and Hewlett, 1982; Gebhardt et al., 2014), but may also increase evaporative losses because of greater exposure of forest soils to solar radiation and wind (Simonin et al., 2007; Traff et al., 2015). A large body of previous research has investigated effects from timber harvesting on water yield (Bosch and Hewlett, 1982; Stednick, 1996; Troendle and King, 1987), with most studies observing increases in stream discharge because of higher runoff from advances in snowpack accumulation and melt, and decreases in stand or catchment level transpiration. While many studies have investigated spatial and temporal soil moisture dynamics at field and catchment scales, most have focused on soil moisture interactions with intact forests, and little previous research is available that directly focuses on timber harvesting. Among available studies that examine the influence of timber harvesting on spatial and temporal soil moisture dynamics, most are focused on historical or conventional clearcutting practices (Chin, 2009; Redding et al., 2003; Adams et a., 1991; Megahan et al. 1982). These effects, in turn, are considered important drivers of increases in runoff after clearcut (CC) harvesting and have been linked to increased sedimentation and higher peak flows that may increase the probability of flooding (Green and Alila, 2012).

Increased attention is being given to the use of alternative harvesting strategies that may offer the ability to reduce the likelihood of negative hydrologic effects. While differing patterns of tree retention strongly control snow accumulation and melt processes (Chapter 2), few past studies have investigated the effects of alternative forest harvesting on patterns of seasonal soil water storage that are influenced by the same factors. Available research on alternative forest harvesting strategies have most often only indirectly evaluated spatial and temporal patterns of SMS in the context of catchment water yield (Robinson et al. 2008), silviculture (Childs and Flint, 1987; Bladon et al., 2006; Heithecker and Halpern, 2006), wildfire management (Ma et al., 2009) or biogeochemical cycling (Barg and Edmonds, 1999; Londo et al., 1999), with exceedingly few studies directly comparing SMS dynamics among multiple alternative strategies in the same setting. Moreover, comparison between existing studies is limited by a lack of standardized methods among studies, harvesting methods, forest stand types, and levels of retention, and the physiographic settings where each was conducted. Consequently, comprehensive efforts are needed to further improve our understanding of the effects of specific alternative harvesting strategies on seasonal SMS dynamics to more accurately predict hydrologic responses to timber harvesting in the context of integrated forest-watershed management strategies and climate change adaptation.

Accordingly, this study was conducted with the broad objective of evaluating the influence of several alternative harvesting strategies on seasonal soil moisture dynamics and exploring how these different strategies affected the specific environmental factors regulating spatial and temporal patterns in soil-water balance over two years. Specific objectives were focused on answering two broad research questions: (1) how do different harvesting strategies impact spatial and temporal patterns of soil moisture storage; (2) what are the primary controlling factors affected by harvesting that are responsible for driving observed differences. Since spatial patterns of soil moisture controlled by feedbacks between soil, topography, and vegetation properties (Rodriguez-Iturbe et al., 1999), I hypothesized that spatially variable feedbacks between these factors and harvest-cutting patterns would create corresponding variation in soil water storage, predicting that SMS would be higher in harvested sites than residual forest stands, and lower on south-facing slopes than north-facing slopes due to higher solar insolation.

3.2. Study area

Research was carried out in the Crowsnest Pass in southwestern Alberta's montane forested front range of the Rocky Mountains. Study sites were located within three sub-catchments (Star West, Star East, and McLaren) of the Star Creek watershed (49° 37' N; 114° 40' W), 7.5 km southwest of the town of Coleman, Alberta, Canada (Figure 3-1). Together with several surrounding watersheds, Star Creek comprises part of a network of catchments that form the Southern Rockies Watershed Project research area, a long-term research project operating since 2004. Star East (389 ha) and Star West (463 ha) sub-catchments form two upper branches of Star Creek and are met by McLaren Creek (95 ha), a seasonally intermittent stream, a short distance below their confluence (Figure 3-1). Star Creek (1855 ha) enters the Crowsnest River forming part of the upper Oldman River watershed. Elevation of the Star Creek watershed ranges from 1475 m to 2631 (Silins et al., 2016), with upslope contributing areas of Star East and West sub-catchments extending into subalpine and alpine zones, whereas the upper sub-alpine portion of McLaren Creek does not does not extend into alpine zones.

Basin mean annual precipitation ranges from 800-1360 mm, approximately 50% of which arrives as snow (Silins et al., 2016; Silins et al., 2009). Snow-melt is a primary contributor to annual discharge in Star Creek. Mean annual temperatures in the region range from –6.4 °C in January to 14.3°C in July (Environment and Climate Change Canada, 2018), however winter air temperatures frequently exceed 0 °C with chinook winds contributing to mid-winter melt periods and rain-on-snow events (Nkemdirim, 1996). Prevailing winds in the Crowsnest Pass are from the west with relatively high wind speeds averaging approximately 18km/hr or more (Alberta Agriculture and Forestry, 2003). Montane forest covers most of the basin at elevations <1900 m with forest cover in the harvest area dominated by lodgepole pine (*Pinus contorta*), as well as lower proportions of white spruce (*Picea galuca*) and Douglas fir (*Pseadotsuga menziesii*). Understory vegetation varies throughout the catchment from moss- and shrub-dominated ground cover in heavily forested sites, to grass-dominated cover in more open areas including forests on south-facing slopes and clearcut sites. Soils within the catchment are a mix of Eutric and Dystric Brunisols with sandy loam or sandy clay loam textures in the top 60 cm, with an increasing proportion of coarse fragments with depth below 20 cm. Soils are underlain by Cretaceous shale, sandstone, mudstone, and limestone (Bladon et al., 2008).

3.3. Materials and methods

3.3.1. Harvest Treatments

Timber harvesting took place in 2015 with separate harvest strategies implemented in each sub-catchment: clear-cut with tree retention (CC) in Star West; strip-shelterwood (SS) in Star East; and a partial-cut (PC) harvest in the McLaren sub-catchment (Figure 3-1; Figure 3-2). CC harvesting consisted of complete stand removal with 15% distributed single-tree and patch-retention within harvested units, over a total area of 69 hectares. Harvesting was divided across south- and north-facing slopes on either side of the Star West drainage, with a 14 ha. northerly aspect unit and a 55 ha. southerly aspect unit. Stand structure of the unharvested retention forest differed moderately between north/south aspects with north-facing stands consisting of higher density, evenly aged, mature lodgepole pine, compared to lower density south-facing stands that had longer live crowns and intermittent gaps or openings between 0.5 – 1 tree heights (H) in size. SS harvesting involved removal of approximately 50% of pre-harvest timber consisting of parallel, alternating clear-cut and forested retention or shelterwood strips approximately 35 m (~ 2H) in width, running from east to west. Strip orientation and width were selected based on the prevailing north-facing slope orientation and stand height to maximize the influence of slope aspect and cutting pattern on snow accumulation and solar insolation after Golding and Swanson (1978). Total harvested area for the SS harvest was approximately 43.8 ha. PC harvesting was carried out over an area of approximately 56 hectares with selective logging of approximately 59% of stems leaving remaining trees either in groups or uniformly distributed. Evaluation of PC harvesting in this study focused exclusively on the uniform-selection harvest units.

3.3.2. Seasonal Soil Moisture

Spatial-temporal patterns of soil moisture storage (SMS) were evaluated using a paired treatment-reference design. Patterns of SMS for each harvest type (CC, SS, PC) were compared with adjacent, fully-stocked, mature forest “reference” stands from the same sub-catchment using fixed, linear SMS measurement transects. Thus while multiple reference stands were studied, unless specified forested reference sites will be described inclusively, though statistical comparisons between harvested-reference transects are based on data from the closest matching reference stands in each respective harvest/subcatchment.

Survey transects consisted of a series of permanent soil moisture sampling points offset approximately 5 metres and parallel to those used for measuring winter snowpacks in Chapter 2, with measurement points marked by vertical painted stakes. Transects across all harvests/sub-catchments were located over a similar elevation, ranging from 1575 m.a.s.l. to 1675 m.a.s.l. (Table 3-1). Transect length and measurement point density varied among harvest treatments to reflect differences in spatial variation in canopy structure among treatments, as follows:

4) CC: sampling points were located along eight transects, four on each of south and north facing slopes, with transects distributed between harvested and reference sites on both upper and lower hillslope positions. Each transect consisted of 6-12 sampling points spaced 7-10 metres apart. Several transects (Figure 2-1) incorporated sampling points that included harvest:forest transition zones, however data from these points were excluded from the final analysis in order to avoid confounding influence from “edge” effects.
5) SS: seasonal and spatial patterns of SMS were captured using two transects, established approximately 100 meters apart and running perpendicularly downslope. Each consisted of 42 sampling points (84 total) bisecting three harvested strips and three shelterwood strips. Points were spaced approximately five meters apart such seven measurement points were distributed equally from edge-to-edge of each forested and harvested strip that (see Figure 3-7).

6) PC: 41 sampling points were distributed between both the harvest and nearby forested reference, with 21 points in the harvested site and 20 points in the forested site. Sampling points in the reference site were distributed evenly between two parallel transects, while those in the harvest area were divided into four shorter "transect segments" to avoid a logging haul road and maintain a consistent hillslope aspect.

Soil moisture was measured using the Time Domain Reflectometry (TDR) method. TDR soil moisture probes at each sampling point consisted of 25 cm and 65 cm stainless steel waveguides made from 0.25-inch, stainless steel rod that were installed in parallel pairs at depths of 20 cm and 60 cm respectively. A wooden jig was used during installation to maintain 5cm parallel spacing between waveguides at each depth, while leaving 5 cm centimeters of additional length above the ground surface for connection to a Tektronix 1502c cable tester. Using the cable tester, the apparent travel distance of the EM wave through the stainless-steel rods was measured at each point every 14-21 days throughout the snow free period in 2016 and 2017 (May to October). Depth integrated volumetric water content was calculated from field measurements with the cable tester after Topp et al. (1980), using the empirical equation derived by Ferre et al. (1996).

$$\theta = 0.1181\,K^{1/2} - 0.1841 \qquad (1)$$

In which:

$$K^{1/2} = \frac{(l_2 - l_1)}{L_{total}} \qquad (2)$$

Where $K^{1/2}$ is the square root of the TDR-measured apparent dielectric permittivity of the soil; $(l_2 - l_1)$ is the apparent travel distance measured with the cable tester, in which l_1 is where the waveguide enters the soil, and l_2 is the reflection from the end of the waveguide; L_{total} is the actual length of the waveguide (20 or 60 cm).

Volumetric water content was converted to SMS (mm) by multiplying θ by the measurement depth (20 cm or 60 cm), where 20-60 cm storage was calculated by subtracting 0-20 cm SMS (mm) from 0-60 cm SMS (mm) measured at the same location. The relationship between TDR-measured K and soil moisture (Eq. 1) was confirmed with physical water content measurements obtained from volumetric cores collected at each site from 0-20 cm depth. Deeper volumetric soil samples could not be collected due to the extensive presence of large cobbles and resulting difficulty of obtaining fixed volume soil cores. However, correspondence between TDR measured (0-20 cm depth) and field measured θ from volumetric sampling showed strong agreement at R^2=0.89 (n=11, p<0.001). Influence of forest floor organic matter (OM) likely resulted in the slight discrepancy between measured and predicted θ (Eq. 1) because OM has a lower dielectric permittivity than mineral soil (K_a ~1.01 vs 3 - 6). Generally, organic soils have a unique calibration equation different from Eq. 1. Attempts were made to correct for the influence of the surface organic layers using a dielectric mixing model but were unsuccessful because of uncertainty in the actual dielectric permittivity and bulk density of the OM. Surface organic matter thickness, measured at each sampling point, was therefore evaluated as an independent controlling variable.

In addition to the TDR measurements, continuous soil moisture (θ) at selected locations was logged using in-situ capacitance soil moisture probes (Decagon/Meter 5TM), installed at 5, 20, and 60 cm depth at representative locations in each harvested and forested reference. Data were logged at 20-minute intervals over several months during the 2017 growing season (recorded using Decagon EM50 dataloggers), and converted to a daily mean θ.

3.3.3. Climatic variables controlling seasonal SMS

Precipitation including snowfall was measured with tipping-bucket gauges at a network of long-term climate stations located throughout the catchment (Figure 3-1). Missing precipitation data (due to data logger/equipment malfunction) for some days were gap-filled using the approach described by Ahrens (2006). Seasonal patterns of air temperature were evaluated from two meteorological stations located at representative elevations within the catchment. Missing data for several dates here were gap-filled using a linear regression approach, given air temperature data between the two stations where closely correlated (R^2=0.99, p<0.001). Variation in seasonal water balance between study years (Figure 3-3) was assessed using by calculating potential evapotranspiration (PET) for each month using the Hargreaves evapotranspiration equation (Hargreaves and Allen, 2003) after Pina (2013).

Differences in microclimate between SS and PC harvests and each corresponding forested reserve were assessed during 2017 using paired meteorological stations measuring hourly wind speed and direction (R.M. Young wind monitor, model 05103), air temperature and relative humidity (Campbell Scientific HMP50) controlled by Campbell Scientific CR-1000 data loggers. Due to project constraints, microclimatic data were not collected locally at CC harvest sites. Davis tipping bucket rain gauges equipped with HOBO™ pendant event loggers were installed in each harvest area during early late spring of 2017 to evaluate coarse differences in precipitation among individual sites, however prolonged drought conditions resulted in insufficient recorded events to provide data for an accurate assessment.

Peak snow water equivalent (SWE) was estimated using snow core measurements taken adjacent to each soil monitoring point in 2016 and 2017 with a standard Federal Corer following methods described in Chapter 2.

3.3.4. Topographic indices and surface solar radiation

Slope, aspect, and elevation were determined by recording the position of transect points using a handheld GPS, then mapping and extracting respective values from a 1m resolution Light Detection and Ranging (LiDAR) Digital Elevation Model (DEM) of the Star Creek basin in ArcGIS (version 10.5, ESRI). Topographic wetness index (TWI) was calculated by estimating the upslope contributing area for each sampling point, then applying the D-infinity algorithm in TauDEM after Tarboton (2003).

$$TWI = ln\left[\frac{a}{tan\beta}\right] \qquad (3)$$

Where a is the upslope area draining through the specified point per unit contour length, and β the local slope angle.

Influence of CC and SS harvests on spatially variable solar radiation and energy forcing was estimated using a Digital Surface Model (DSM) incorporating catchment topography, and the height and position of post-harvest residual trees. The DSM was developed using LiDAR point data of individual tree positions and heights prior to harvest collected by AB. Agriculture and Forestry, and removing trees located in harvested areas (i.e. setting tree heights inside harvested polygons to zero (ground level). "Post-harvest" point data were then converted to raster format with cell dimensions set equal to mean crown width (2.2 meters) estimated using relationships between lodgepole pine height and canopy width after Fish et al. (2006). This produced a DSM approximating residual stand canopy and harvested ground surfaces present in CC and SS harvested sites including their respective land surface topography (slope, aspect, and elevation). Since harvest polygons did not include the position of single-tree retention trees dispersed through PC area, this approach was restricted to only CC and SS harvests. Using this DSM, potential cumulative incoming radiation was calculated for each transect point for the 30-days preceding each measurement date using standard solar radiation modeling functions in ArcGIS 10.5. Tools for modelling ground/snow surface solar radiation in GIS cannot currently incorporate transmission of radiation through tree canopies (Bode et al., 2014) creating an opaque canopy surface that likely underestimates ground-level incoming radiation in areas shaded by retained trees because some shortwave radiation transmission through the canopy would not be represented using this approach. However, this analysis provides a meaningful representation of canopy and topographic shading that would describe the majority of harvest effects on incoming shortwave radiation and their spatial variability among harvest cutting-patterns.

3.3.5. Topography indices and surface solar radiation

Soil physical properties (Table 3-1) were assessed from a soil pit dug in each harvest and reference site (Figure 3-1). At each soil pit volumetric cores were collected at 0-20 cm depth, while non-volumetric samples were collected below this depth because to the large number of coarse fragments that made volumetric coring impractical. Composite samples for 0-20 and 20-60 cm depth increments were sieved to 2mm, oven-dried, and assessed for texture using the Bouyoucos hydrometer method (Kroetsch and Wang, 2007) to determine percent sand, silt, and clay (Table 3-1), and corresponding textural class.

Canopy closure (%) was measured using from vertical hemispherical photos that were taken along soil sampling transects points within treed sites including all reference sites, as well as SS and PC harvests. No photos were collected from either north or south facing CC sites because no overhead canopy was present. Images were collected in the field using a Nikon D90 DSLR camera with Sigma 180° fish-eye lens, mounted on a leveled tripod set at breast height (1.3 meters).

Images were captured using optimal settings outlined by Chianucci and Cutini (2012), and canopy openness quantified using Gap Light Analyzer (GLA) (Frazer et al., 1999). During processing with GLA, hemispherical photos were reduced from a 180° to 90° field of view improve measurement of direct overstory canopy by excluding distant trees. Ground vegetation cover was also quantified using the Daudenmire method (Coulloudon, 1999) with ground cover classes estimated using a 0.5 m x 0.5 m square quadrat constructed from 12.5 mm (0.5 inch) diameter PVC pipe centred on each transect point.

3.3.6. Data Analyses

A post-hoc, comparative analysis of paired harvest and reference sites was used to test the effect of specific harvesting strategies on soil water dynamics. Assumptions of normality and equal variance were assessed using Shapiro-Wilk's test and Levene's test as well as visual examination of plotted residual, QQ-plots. Data from repeated measurements of SMS did not meet homogeneity of variance/compound symmetry assumptions even after data transformation, thus differences in SMS within harvests and respective reference areas were tested individually for each sampling date/period using one-way analysis of variance (ANOVA). Post-hoc pairwise comparisons of SMS between harvested and corresponding reference sites were made using the Games-Howell test, which includes no assumption of equal sample-size and variance (Toothaker, 1993).

Temporal stability analysis has been widely used to evaluate the reliability of point-scale measurements at representing areal mean soil moisture (Grant et al., 2004; Grayson and Western, 1998; Kampf et al., 2015; Martinez Garcia et al., 2014; Vachaud et al., 1985; Williams et al., 2009), and was therefore used as an additional non-parametric test to assess differences over time: (1) between all harvest and reference sites; (2) of spatial patterns of SMS observed across harvested and forested strips. In the first case, this was done by calculating the relative difference between treatment/reference and basin mean SMS for each observation date:

$$\delta_{ij} = \frac{S_{ij} - \bar{S}_j}{\bar{S}_j} \qquad (4)$$

where S_{ij} is mean SMS for harvest or reference i at time j, and $\bar{S}_j$ is basin mean SMS calculated as the grand mean of all harvest/reference site means on each sampling date (to eliminate influence from different sample sizes). Mean overall relative difference was then calculated for each treatment or reference across all sampling dates (j=15) where transects were free of snow:

$$\bar{\delta_i} = \sum_{j=1}^{i=14} \delta_{ij} \qquad (5)$$

The same calculation was applied to patterns of SMS in the SS harvest, but with relative differences assessed between mean SMS at each relative position across the width of harvested and forested strips (see Figure 3-7, n=6), and the overall mean of all sampled points in the strip-harvest (n=84). Spearman's Rank correlation test was used to evaluate the temporal stability of observed differences in SMS across all snow free dates between all harvest/reference sites, and spatial patterns of SMS across the width of harvested strips. Relative differences in SMS within each harvest/reference pair calculated for each date were tested using Student's paired t-test.

The influence of static but spatially varied controls (slope, aspect, elevation, TWI, peak SWE, canopy, vegetation, OM thickness) were assessed using Pearson's product-moment test to evaluate the correlation of these factors with spatial patterns of SMS measured on each observation date, as well as averaged over the total duration of the study. Differences in mean microclimate variables in the SS, and PC harvests with reference stands were assessed using simple linear regression. All data analyses were conducted in R (R Core Group, version 3.4.3, 2017; R-studio, version 1.1442, 2017), using a value of α=0.05 as the threshold for statistical significance.

3.4. Results

3.4.1. Precipitation and climate during the study period

Data from the gauging network in Star Creek show 877 mm and 822 mm of precipitation (P) were received during each water year, (defined here as November 1 to Oct 31 because SMS measurements were collected from May 1 to October 31of each year) in 2015-2016 and 2016-2017, respectively. Seasonal patterns of P differed markedly between years despite similar annual, total amounts. Snowpack peak SWE in 2015/16 (79 mm) was 35% below the average for Star Creek from 2009-2018, while in 2016/17 (195 mm) was 59% greater than average. Inversely, growing season P (received from May 1-October 31) was slightly above average in 2016, contributing 485 mm or 55% of the annual total, however in 2017 was only 304 mm or 37% of the total for that year. Variation in the temporal distribution of precipitation and air temperature produced notable differences in monthly potential evapotranspiration (PET) between the 2016 and 2017 growing seasons (Figure 3-3).

Overall patterns of soil moisture strongly demonstrated the influence of annual wetting and drying cycles in both years with continuous mean soil moisture content measured at 5, 20, and 60 centimeters, and repeated transect measurements at 0-20 cm and 20-60 cm all showing corresponding temporal SMS responses (Figure 3-4, Figure 3-5). Continuous measurements showed volumetric water content at the 5 cm depth was highly responsive to prevailing temperatures, PET, and precipitation events, while θ at 20 cm and 60 cm responded more gradually (Figure 3-4). SMS in each year was highest at the start of the season, following spring melt, and lowest in late summer (July and August). Contrasting patterns of seasonal precipitation and climate in each year were strongly reflected by changes in overall mean SMS from the beginning to end of the snow-free (growing season) period in each measurement year (May 1-Oct 31) (Table 3-2). Basin mean SMS in 2016 changed by +7.4 mm and -2.8 mm in the 0-20 cm and 20-60 cm depths respectively, however in 2017 SMS at the same respective depths declined (-29.6 mm, and -44.7 mm) due to prolonged drought conditions.

3.4.2. Effects of alternative harvesting strategies on SMS

Overall results showed harvesting had a significant effect on SMS with mean SMS in harvested sites averaging 20% and 17% higher than in forested reserves in the 0-20 and 20-60 cm depths, respectively. However, results also showed differences varied strongly across harvesting methods, observation dates, and study years. Among alternative harvesting methods, overall SMS increased in the CC harvest by ~25%, ~39% in the SS, and ~19% in the PC compared to their respective reference stands. Mean SMS in 0-20 cm and 20-60 cm in 2016 were consistently higher across all harvested sites regardless of cutting pattern or slope-aspect, but in 2017 were widely reduced and varied strongly between alternative strategies because of different responses to prolonged drought conditions that depleted soil moisture across the basin (Figure 3-5).

While SMS was generally greater in harvested areas of all three harvested sub-catchments compared to reference stands, the temporal pattern of harvest-associated increases in SMS varied among these harvesting strategies (Table 3-3). Significantly greater surface (0-20 cm) SMS in CC harvested compared to reference transects was most clearly evident in 2016 and was more consistently observed on south facing CC sites where differences occurred primarily from July to September (p=0.001-0.041) but were not present in early or late months. Corresponding differences in SMS in 20-60 cm soil layers (p=0.018-0.05) did not follow a discernable trend and were only significant on 1/7 and 3/7 observation dates for north and south aspects respectively. CC SMS was not statistically different on any observation date in 2017 regardless of soil layer depth or slope orientation (p=0.095-0.999) but showed a consistently greater SMS in the 20-60 cm depth on the north-facing CC which was most frequently lower than the adjacent forest (Table 3-3). SMS of the surface 0-20 cm soil layer in the SS harvested sites was significantly greater than reference stands on all observation dates (p<0.001) with relative differences showing SMS in harvested-strips was twice as high compared to forested reserves during low seasonal soil moisture conditions from July to September (Table 3-3). SMS in the deeper 20-60cm soils in harvested SS sites was also significantly higher on all but two observation dates (p<0.001). SMS in SS sites in 2017 was significantly higher for both soil layer depths on all observation dates that followed disappearance of snow from harvested-strips (June 6 onwards) (p=<0.001-0.033). On a single measurement date in the fall of 2016, SMS in PC sites was not statistically different from reference stands in the surface 0-20 cm depth soil layer (p=0.859) but was significantly greater in the deeper 20-60 cm depth layers (p<0.001). In 2017, SMS in the surface 0-20 cm layer of PC sites did not differ significantly on any date (0.715-1.0) but was significantly greater in the deeper 20-60 cm layer except at the start and end of the season (p<0.001-0.032).

Time stability analyses (Figure 3-6) showed SMS at 0-20cm depth was consistently greater in CC and harvested-strips, but highly variable in both the PC and corresponding reference site located in McLaren Creek. SMS in the deeper 20-60 cm depth layers were consistently greater in all harvested sites except the north-facing CC. Corresponding Spearman's rank correlations (Table 3-4) showed the relative difference in SMS among all harvests and reference sites were highly stable in the surface 0-20 cm soil depth layers (0.88, p<0.05 on 85% of dates), and moderately stable in deeper 20-60 cm depth layers (0.66, p<0.05 on 42% of dates). Student's t-test results indicate SMS was significantly increased in each harvested treatment at both soil depths except at 0-20 cm in the PC (p<0.001) and 20-60 cm in the north facing CC (p<0.05).

SS harvesting resulted in highly distinct spatial and temporal patterns of SMS across the width of harvested and forested strips (Figure 3-7). SMS was consistently greater within harvested strips and lower in the adjacent unharvested reserve stands. While these temporal patterns appeared somewhat stronger earlier in the growing season, elevated SMS in harvested strips was evident throughout the growing season in both surface and deeper soil layers. Although SMS fluctuated substantially in response to seasonal and drying and re-wetting cycles across 2016 and 2017, time-stability analysis showed differences between storage at each relative position were highly stable throughout both years. Mean Spearman coefficients were 0.91 for 0-20 cm depth SMS with all dates significantly correlated ($p<0.01$), and 0.76 for 20-60 cm SMS with >95% of all observation dates significantly correlated ($p<0.05$). In CC, and PC harvested sites, the spatial patterns of SMS were also stable ($p<0.05$) but not clearly correlated to residual tree cover.

3.4.3. Spatial and temporal controls on SMS

Evaluation of microclimatic data in both the SS and PC harvested areas indicated no significant differences in air temperature and humidity with adjacent mature forest stands. Mean daily wind speed was significantly higher in both harvested sites, with wind in harvested-strips approximately 70 % higher than forested strips (1.0 m/s ± 0.5 vs. 0.59 ± 0.3), and approximately 120% greater in the PC site compared with that measured above the adjacent forest (1.1 ± 0.6 vs. 0.5 ± 0.2) ($p<0.05$).

Results assessing topographic, and environmental controls on SMS using Pearson's product moment correlation are summarized in Table 3-5. Among all factors, peak SWE and elevation showed the strongest and most consistent correlation with patterns of SMS. Peak SWE was significantly positively correlated to 0-20 cm SMS on all sampling dates ($p<=0.05$), with maximum correlations of +0.59 and +0.43 in 2016 and 2017 respectively. Peak SWE was also significantly correlated to 20-60 cm SMS on all but the first and last observations in 2016 ($p<=0.05$), but only 4 of 10 dates in 2017; primarily during summer. Elevation was significantly positively correlated with surface 0-20 cm SMS on 14 of 15 observation dates, with a maximum correlation of +0.54 ($p<0.001$). Other positive [+] or negative [-] relationships with surface 0-20 cm layer SMS (maximum correlation, and number of significantly correlated observations) included canopy closure (-0.55; 14), and slope (-0.22; 8). TWI was weakly but significantly negatively correlated with SMS across 11 of 15 dates which is inversely proportional to the empirical relationship on which it is based. All other variables were non-significant, or weakly and inconsistently correlated to 0-20 cm storage. Elevation was significantly correlated with deeper 20-60 cm layer SMS on 10 sampling dates with a maximum correlation of +0.39. While the strongest correlations between the same soil layer and peak SWE were +0.62 and +0.24 in 2016 and 2017, respectively. Other meaningful correlations between deeper SMS included canopy closure (-0.38; 8), aspect (-0.29; 8), and slope (-0.41; 6). All other variables were either non-significant or weakly and inconsistently correlated to SMS at both layer depths.

No clear correlations were evident between estimated solar radiation and patterns of SMS (Table 3-6) in north and south facing CCs or harvested-strips because correlations were either insignificant or inversely related to the empirical relationship between radiation and SMS. When evaluated across both CC and SS harvests inclusively, radiation was significantly correlated to 0-20 cm storage on nearly all observation dates in 2016 (p=0.05), but only one date in 2017, while 20-60 SMS was significantly correlated to solar radiation on 7/17 dates across both years.

3.5. Discussion

3.5.1. Influence of regional climate seasonality

Broad temporal patterns in SMS across both harvested and reference stands were primarily driven by higher order climatic controls exerted by precipitation, air temperature, and PET corresponding to annual wetting and drying cycles (Table 3-2 and 3-3; Figures 3-3 to 3-5). Prevailing climatic conditions control SMS by regulating the balance of water inputs from P and losses from PET (McMillan and Srinivasan, 2015; Odorico et al., 2000; Rodriguez-Iturbe et al., 1999). Wetting and drying cycles in each year could be categorized into three phases that corresponded similarly to those described by Williams et al., (2009) and Chin (2009): (1) Spring wetting characterized by high SMS on early observation dates driven by recent snowmelt; (2) Drying, caused initially by soil water percolation and lateral transfer, and later by high summertime PET leading to annual SMS minima in late summer/early fall; (3) Re-wetting in mid-late autumn, with some degree of soil moisture recharge occurring due to cooling temperatures and rainfall prior to winter (Figure 3-5, Table 3-3).Soil moisture seasonality in this study is consistent with past research that has shown prevailing weather and climate dominantly regulate temporal patterns of

SMS over more spatially-varied but static factors such as topography, soil properties, and forest/vegetation cover (Brocca et al., 2012; Williams et al., 2009; Wilson et al., 2004; Zucco et al., 2014). However, while temporal stability analysis does not appear to have been previously applied to research on SMS and forest harvesting, these findings are consistent with those of Zucco et al. (2014) who showed that differences in land cover had a larger influence on spatial variation of soil moisture than higher order climatic controls regulating temporal variation in SMS.

3.5.2. Harvesting effects on spatial and temporal SMS

Overall results in this study showed that despite large seasonal fluctuations in SMS, soil moisture storage was generally greater in harvested areas for all three alternative harvesting approaches. Field surveys and corresponding time stability analysis showed harvested sites from all harvest types generally maintained higher seasonal SMS (Table 3-3; Figures 3-5 & 3-6). This is consistent with results of many other studies that have also reported generally similar increases in soil moisture after harvesting (Adams et al., 1991; Anderson and Burt, 1977; Bethlahmy, 1962; Bladon et al., 2006; Breda et al., 1995; Gebhardt et al., 2014; Keppeler et al., 1994; Megahan, 1983). Increases in SMS have been found to occur primarily due to reduced stand-level transpiration and increased throughfall (Bethlahmy, 1962; Bosch and Hewlett, 1982; Chen et al., 1993; Famiglietti et al., 2008; Gebhardt et al., 2014; Spittlehouse et al., 2004; Teuling and Troch, 2005; Wilson et al., 2004). While increases in SMS observed here can be broadly attributed to these same effects (though not explicitly measured in this study), quantitative comparison of effects from the three harvest strategies in this study with those reported elsewhere (largely from CC harvesting) is only possible in general because variation in soils, climate, precipitation, and tree species composition regulates the actual magnitude of harvest effects on SMS in different forest regions. However, this study does enable direct comparison of all three alternative harvesting strategies in the study region and showed critical differences in how each harvesting method influenced spatial and temporal patterns of SMS (Table 3-3, Figure 3-5).

Across both study years, increased SMS after harvesting was greatest in SS (39%) followed by CC (~25% across both north- and south-facing hillslopes), and PC (~19%) for the two soil layers considered (0-20, and 20-60 cm). For the more commonly used CC harvest, hillslope aspect was an important factor where SMS at 0-20 cm depth averaged 21% and 25% higher in respective north and south facing sites, and 24% higher at 20-60 cm depth in the south-facing site. These increases were moderate compared to other related research. Chin (2009) for example found 0-20 cm soil moisture was 11% higher in CC stands than retained forest, while Megahan (1983) found soil moisture increased by 40% after clearcutting of ponderosa pine in Idaho, USA. Direct comparisons with other studies on CC harvesting are complicated by differing methods used to quantify changes in soil moisture content, but varying increases in SMS after clearcutting have also been described by a number of other researchers (Adams et al., 1991; Bethlahmy, 1962; Dhakal and Sidle, 2004; Redding et al., 2003). Reasons for lack of difference in SMS in the deeper 20-60 cm soil layer (harvested vs. reference) in the north-facing CC are unclear but may be due to confounding differences in subsurface drainage and lateral transport where north-facing reference transects included forest in the riparian buffer bordering Star Creek. SMS in SS harvested-strips averaged 40% and 37% higher at 0-20 cm and 20-60 cm depths respectively, comparable to the upper range of values reported in literature on conventional clearcutting (Megahan, 1983). Results showing SMS in harvested-strips were more than twice as high as in forested-reserves during summertime moisture minima exceeded any maximum increases after harvesting reported by any other studies. While few other studies have explicitly measured SS soil moisture dynamics, results of this study strongly corroborate observations by both Dunlap and Helms (1983) and Childs and Flint (1987) who found harvested strips maintained higher moisture levels than adjacent forest stands due to reduced rates of soil evaporative loss. Mean SMS in the PC harvest averaged 19% higher at both 0-20 cm and 20-60 cm depths over the duration of the study; however, differences were only statistically significant in the deeper layer. Effects from PC harvesting in this study relate closely to findings from Gebhardt et al. (2014) who found uniform thinning of 67% basal area increased soil water availability by causing a 50% decrease in stand level transpiration. In contrast, research by Heithecker and Halpern (2006) on PC harvesting at a similar level of retention (40 %) reported no change in surface soil moisture compared to adjacent reference forests, while Zhu et al. (2017) found deeper subsurface SMS increased at the same time as near surface SMS decreased.

Temporal patterns of SMS among all three alternative harvesting strategies responded differently during wetter or dryer periods indicating that specific effects of each method on seasonal SMS were highly dependent on interactions between harvest cutting-patterns (i.e. the spatial arrangement of retained trees), soil depth, and prevailing climatic controls. (Table 3-3; Figure 3-5). TDR measurements in 2016 (corresponding to low spring snowmelt but frequent summer rainfall) showed that SMS in harvested-strips was nearly uniform over the entire season, while SMS in CC soils was elevated but fluctuated seasonally nearly in parallel with that evident adjacent forest reserves. SMS measurements in 2017 (corresponding to a large winter snowpack but prolonged summer drought) showed smaller differences between harvested and forest areas both at the start of the season because of widespread saturation after snowmelt, and after deeper drought conditions that reduced differential rates of water loss between forest and harvests. Previous research has shown differential rates of water loss between harvested and forested sites may diminish with lower soil water availability (Ziemer and Service, 1964). This explanation is supported by transpiration data that were collected concurrently in PC, SS, and references sites in 2017 which showed low soil moisture availability severely limited tree-transpiration through July-September (Karpyshin, unpublished data). However, it is also noteworthy that SMS during the exceedingly dry conditions in August 2017 generally remained elevated over that of reference stands in the both shallow and deeper soil layers for almost all of the harvesting strategies (with the exception of the north-facing CC at 20-60 cm depth). The lack of difference between 20-60 cm SMS in the north-facing CC may be because of differences in subsurface drainage between the harvest and reference site, however more detailed information is needed to verify this. Separately, post-harvest recovery of grasses and herbaceous vegetation may also have created a reduced response signal in 2017 versus 2016. Several studies have noted harvesting effects on SMS may diminish after several years due to vegetation regrowth (Adams et al., 1991; Keppeler et al., 1994), although others have found effects may persist for more than 10 years (Kranabetter and Coates, 2004); further research would be needed to verify the role of recovery on results in this study.

Spatial and temporal patterns of seasonal SMS provide critical information needed to improve prediction of effects from harvesting on catchment runoff processes (Penna et al., 2011; Seyfried et al., 2009), as well as assess available moisture supporting plant growth (Childs and Flint, 1987; Elliott et al., 1998; Liu et al., 2018). Results from this study show that patterns of tree retention may create corresponding variation in patterns of SMS storage, and strongly reinforce past research showing the role of forest cover in controlling spatial and temporal patterns in soil moisture (Tueling and Troch, 2005; Chen et al. 1993; Spittlehouse, 2005; Wilson, 2004; Famiglietti et al., 2008). Research on CC harvesting by Spittelhouse et al. (2005) and Redding et al. (2003) report that soil moisture elevated for a distance of up to approximately one tree-height from forest edges into openings. Transect points in CC harvested sites were typically located more than one tree height away from residual forest stands with no direct cover, resulting in patterns of SMS reflecting other static controls such as soil drainage rather than adjacency to stand edges. However, results from SS harvesting showed clear spatial patterns of SMS persisted across the width of forested and harvested strips (Figure 3-7; Table 3-4). SMS in the surface 0-20 cm was highest on the upslope (shaded) side of harvested strips but declined as it reached the opposite edge, while SMS at 20-60 cm depth was highest in the centre of harvested strips. While no previous studies have directly examining soil moisture patterns in SS harvests, the patterns of SMS in deeper 20-60 cm layers correspond to those reported by Zeimer and Service (1964) who found seasonal soil moisture was depleted at a faster rate in forested plots and progressively decreased toward the centre of openings. Spatial patterns of SMS in PC harvest were not sharply defined, but significant negative correlations between shallow 0-20 cm SMS and canopy cover during indicate that during several summer observation dates moisture decreased with proximity to residual trees. Field observation of root biomass of wind thrown Lodgepole pine in the study area suggest the majority of fine root biomass important in soil water uptake are situated in the surface 20 cm soil layer. Simonin et al. (2007) found that while thinning affected SMS in 0-30 cm deep soil layers, soil moisture results were primarily dependent on climatic conditions and time since harvest, while corroborating observations were reported by Rambo and North (2009).

3.5.3. Factors controlling spatial and temporal SMS

While it was expected the strong difference in solar angle and incident radiation among south- versus north-facing CC slopes would have produced large differences in SMS, only slight evidence for early moisture drawdown on south-facing slopes was observed in 2016 but not in 2017. Results from 2016 corroborate concurrent measurements conducted in each CC unit in the same year reported by an allied study on nitrogen dynamics by Stewart (2018) who found south-facing hillslopes had warmer, dryer soils. Weak evidence for slope orientation effects in this study is in contrast with stronger effects typically described by past research: Geroy et al. (2011) found soil moisture was 25% higher on north-facing slopes than south-facing slopes, while Ebel et al., (2012) observed declines in soil moisture on north-facing burned sites occurred one month later. Reasons for the relative lack of influence from aspect in this study are unclear but may be due to confounding differences in hillslope drainage, as well as more dominant effects from wind and vapour pressure deficit in driving moisture loss during extreme drought conditions in 2017. Alternatively, it is possible that capillary discontinuity between drier near-surface duff/soil layers prevented the significantly greater evaporation that would be expected on south-facing slopes and may have acted as a vapour barrier effectively de-coupling SMS from the larger potential evaporative draft (PET) on these hillslopes. In addition, CC SMS estimates may have been affected by the smaller number of sampling points CC sites contained relative to SS, or PC sites as drier soil moisture conditions have been found to increase coefficients of variation, because of proportionally greater influence from spatially variable differences in soil moisture retention (Heithecker and Halpern, 2006).

Soil texture was generally similar among sites, classified as either sandy loam or sandy clay loam suggesting general consistency in site-level water retention capacities from 0-60 cm depth. Measurements also showed relative differences in surface OM depth between harvest and references sites could not explain increases in SMS, because increases in water content were far higher than could be explained by proportional differences in soil dielectric permittivity between mineral soils and organic matter. Different SMS responses between surface and subsurface layers were unsurprising given near-surface soils (i.e. 0-20 cm) act as a primary nexus for soil-atmospheric water flux, buffering underlying layers from controlling processes including precipitation, temperature, and turbulent vapour exchange (Rosenbaum et al., 2012). As a result, soil moisture is typically highly responsive to prevailing weather conditions at the ground surface but becomes decreasingly so with depth (McMillan and Srinivasan, 2015)(Figure 3-4). Subsurface soil moisture is also more likely to be moderated by groundwater and lateral redistribution processes which could mask or reduce potential effects from harvesting. Field observations of shallow water tables in spring suggest this effect was prevalent during early season observations because snowmelt raised the water table in most sites close to the surface.

Analyses of additional controlling factors (Table 3-5) showed that spatial patterns of SMS at the watershed scale were most strongly correlated with differences in elevation and peak SWE. Elevation influences patterns of moisture by controlling precipitation through orographic processes (lapse rates), topographic drainage, and other factors. It is unlikely that differences in elevation played a substantial role in observed differences in SMS between forested and harvested sites because measurements were conducted across a narrower band of similar elevations. Significant correlations with peak SWE may also be related to orographic effects on precipitation at the catchment scale, however, harvesting patterns likely produced the strongest effects on snowpacks and melt as described in Chapter 2. Past studies that have demonstrated strong spatial interactions between forest cover, snow, and soil moisture (Conner et al., 2016; Ebel et al., 2012; Kampf et al., 2015). Analyses of snowpack dynamics in Chapter 2 showed that shading associated with slope-aspect and the width and orientation of forested-strips created spatial patterns of snowpack accumulation and melt broadly analogous to those observed for SMS in 0-20 cm soil layers suggesting spatial patterns of SMS in the SS harvest are likely the result of near-surface moisture being regulated by the same factors. Analyses did not indicate a significant correlation between incoming radiation and SMS in either SS or CC harvests except when both SS and CC sites were assessed together. Weak correlation between solar radiation and SMS in this study contrast with Redding et al., (2003) who found patterns of soil moisture along clearcut edges were primarily driven by the spatial distribution of solar irradiance. This may be because radiation modeling approaches used here did not provide sufficient spatial discretization and could not incorporate radiation transmission through retained tree canopies; more detailed work is needed to refine this.

Overall, highly variable inter-annual and seasonal patterns in SMS in CC sites suggest clearcutting had the lowest ability to moderate the growing season soil moisture losses, while harvested-strips showed SS harvesting likely had the strongest effect where SMS did not decline as strongly through the growing season. Differences between seasonal patterns of SMS in CC and SS harvests are consistent with reports by Childs and Flint (1987) who found seasonal soil moisture at 0-40 cm depth decreased earlier in CCs compared to SS harvested sites. Differing results between 0-20 cm and 20-60 cm SMS in the PC harvest suggest that thinning is likely to increase deeper soil moisture, but uniformly dispersed patterns of tree retention may not strongly moderate rates of surface soil moisture loss.

3.5. Conclusions

All three harvesting strategies had a significant effect on seasonal SMS, however effects differed strongly between harvest types. Different spatial and temporal patterns of SMS occurred among alternative harvesting strategies because spatial patterns of tree retention produced corresponding spatial differences in seasonal soil-water balance; from water input by snowmelt and rain throughfall; and water lost by tree-transpiration and turbulent vapour exchange.

1. CC harvesting resulted in variable but significant increases in SMS at both 0-20 and 20-60cm depths during periods of higher moisture availability in 2016, however effects from harvesting were reduced during drought conditions in 2017. These results suggest that CC effects on soil moisture may be more susceptible to prevailing climate conditions because of increased exposure to wind and solar radiation.
2. SS harvesting had the largest and most stable effect on SMS, with harvested strips maintaining significantly elevated levels of surface (0-20cm) and subsurface (20-60cm) SMS over respective wet and dry study years. Highly consistent differences in SMS demonstrate that SS harvesting on north-facing slopes may reduce soil-atmospheric water losses even under strongly variable micro-climatic conditions.
3. PC harvesting resulted in significantly increased SMS, but only in deeper 20-60cm soil layers in 2017. These results suggest that while tree removal likely drives increased soil moisture through decreased evaporative losses (precipitation interception and transpiration), uniformly dispersed, lower density residual trees may not offer a strong ability to moderate surface soil moisture loss.

Patterns of SMS were not consistently correlated with measured controlling environmental factors at the site scale but were strongly correlated with elevation and peak SWE at the catchment scale. Different harvesting patterns evaluated here were shown to create strongly differential patterns of snowpack accumulation and melt (Chapter 2), and results from this study suggest the same factors governing harvest effects on snowpacks also likely regulate the differential soil moisture legacy from three harvesting patterns.

Numerous previous studies have demonstrated changes in catchment water yield from forest harvesting associated with the role of forest-cover in regulating soil-atmospheric water-balance (Brown et al., 2005; Hubbart et al., 2007; Stednick, 1996). Differing spatial and temporal pattern of SMS observed in this study are important predictors of how alternative forest harvesting strategies are likely to influence catchment runoff dynamics and forest regeneration success under differing climatic conditions. However, further research that assesses corresponding effects on streamflow is needed to fully evaluate the use of each of these alternative harvesting methods for improving regional integrated forest-water management strategies.

Table 3-1: Summary of site characteristics (mean ± standard deviation) among harvested and references sites. Note: non-zero canopy closure values for Strip-cut are a result of edge proximity rather than presence of a direct overstory.

Harvesting Strategy	Elevation (m.a.s.l.)	Slope (deg)	Aspect	Canopy closure (%)	Veg cover (class)	0-20 cm Sand/Clay (%)	20-60 cm Sand/Clay (%)	Peak SWE (mm) 2016	Peak SWE (mm) 2017
Clearcut N	1598 ± 22	14.6 ± 2.1	N	0 ± 0	2.8 ± 0.8	50/28	54/24	34.7	149.6
Reference N	1644 ± 1	16.7 ± 6.2	N	56 ± 15	3.2 ± 0.4	55/21	58/23	29.4	195.8
Clearcut S	1607 ± 28	7.5 ± 5.1	SE	0 ± 0	3.2 ± 1.4	56/12	52/17	14.8	121.4
Reference S	1594 ± 5	11.3 ± 1.5	SE	46 ± 26	3.9 ± 1.2	60/13	57/15	16.9	177.4
Strip-cut	1652 ± 14	11.4 ± 2.5	NNE	9 ± 11	2.8 ± 1.3	54/14	52/19	187.9	325.2
Strip-forest	1647 ± 11	11.9 ± 1.8	NNE	51 ± 8	2.3 ± 1.0	51/15	52/19	57.4	207.6
Partial-cut	1603 ± 15	14.9 ± 2.0	N	27 ± 17	3.3 ± 1.2	59/15	59/23	–	230.7
Partial-cut Ref	1580 ± 4	7.3 ± 2.0	N	57 ± 5	3.2 ± 1.0	61/9	48/23	–	180.7

Table 3-2: Annual (water year) precipitation, peak winter SWE, and growing season precipitation, PET, and change in soil water storage in 0-20 and 20-60 cm depth soil layers measured in Star Creek during this study. All values are in millimeters

			Growing season (May 1 to Oct. 31)			
					Mean change in storage	
Water year (Nov 1. to Oct. 31)	Total annual precipitation	Catchment Peak SWE	Precipitation	PET	0-20 cm	20-60 cm
2015/16	877	79	485	507	+7.4	-2.8
2016/17	822	195	304	556	-29.6	-44.7

Table 3-3: Mean soil water storage (mm) of harvested sites ± standard deviation for all survey dates, and ratio of harvest:reference storage. Values in bold are significant at α=0.05 with respect to SMS measured in reference stands on the same observation date.

Depth (cm)	Date	Clearcut N		Clearcut S		Strip-shelterwood		Partialcut		All	
		Storage (mm)	Ratio	Storage (mm)	Ratio	Storage (mm)	Ratio	Storage (mm)	Ratio	Storage (mm)	Ratio
	2-May-16	74.2 ± 13.0	1.15	**61.8 ± 13.7**	**1.35**	**78 ± 15.2**	**1.31**	–	–	71.4 ± 14	1.15
	26-May-16	78.4 ± 12.8	1.21	70 ± 18.2	1.17	**77.1 ± 15.2**	**1.20**	–	–	75.2 ± 15.5	1.13
	17-Jun-16	62.2 ± 12.0	1.35	**50.3 ± 12.6**	**1.50**	**72 ± 14.7**	**1.61**	–	–	61.6 ± 13.1	1.31
	12-Jul-16	**49.2 ± 13.6**	**1.65**	**39.8 ± 13.1**	**1.46**	**64.6 ± 16.2**	**2.14**	–	–	51.2 ± 14.3	1.54
	9-Aug-16	**47.5 ± 15.4**	**1.77**	**40.5 ± 15.2**	**1.51**	**68.9 ± 18.2**	**2.20**	–	–	52.3 ± 16.3	1.59
	9-Sep-16	**51.2 ± 15.3**	**1.98**	**37.2 ± 10.4**	**1.40**	**70.4 ± 22.3**	**2.48**	–	–	53 ± 16	1.74
	22-Oct-16	77.1 ± 17.5	1.15	73.9 ± 19.9	1.14	**81.4 ± 13.7**	**1.26**	61.8 ± 12.1	1.08	73.6 ± 15.8	1.12
	6-May-17	90.9 ± 15.4	0.88	80.1 ± 18.5	1.08	79.4 ± 13.4	1.05	94.6 ± 13	–	86.2 ± 15.1	1.00
0-20	19-May-17	89.4 ± 22.8	1.12	76.6 ± 17.4	1.10	83.5 ± 18.4	1.03	81 ± 22.7	1.15	82.6 ± 20.3	1.07
	6-Jun-17	87.4 ± 18	1.26	66.8 ± 25.2	1.24	**98.6 ± 17.7**	**1.37**	48.9 ± 16.8	1.09	75.4 ± 19.4	1.19
	24-Jun-17	72.2 ± 18.1	1.28	58.5 ± 20.1	1.45	**89.4 ± 19.5**	**1.44**	32.3 ± 16.8	1.21	63.1 ± 18.6	1.24
	12-Jul-17	64 ± 22	1.38	52 ± 18.8	1.17	**73.4 ± 22.2**	**1.42**	37 ± 14.4	0.94	56.6 ± 19.4	1.19
	25-Jul-17	39.5 ± 12.5	1.46	34 ± 16.1	1.25	**51.6 ± 20.1**	**1.34**	14.1 ± 8.3	0.98	34.8 ± 14.2	1.22
	7-Aug-17	49.5 ± 17.8	1.29	35.7 ± 16.6	0.93	**53.4 ± 20.8**	**1.29**	21.7 ± 10.2	1.21	40.1 ± 16.4	1.20
	24-Aug-17	42.7 ± 13.9	1.23	37.8 ± 13	1.20	**53.7 ± 22.7**	**1.38**	15.9 ± 9.2	1.13	37.5 ± 14.7	1.20
	28-Sep-17	47.7 ± 9	1.32	40.7 ± 12.6	1.18	**47.8 ± 18.7**	**1.45**	18.6 ± 11.1	0.82	38.7 ± 12.9	1.17
	21-Oct-17	61.0 ± 16.3	1.15	61.6 ± 21.4	1.09	**69.5 ± 19.1**	**1.36**	38 ± 12.7	0.82	57.5 ± 17.4	1.09
	Mean ± S.E.	63.8 ± 4.1	1.25	54 ± 3.8	1.21	71.4 ± 3.4	1.40	42.2 ± 6.5	1.19	59.5 ± 3.9	1.20
	2-May-16	93.9 ± 21.7	1.08	**124 ± 68.5**	**1.46**	**107.2 ± 28**	**1.20**	–	–	108.4 ± 39.4	1.08
	26-May-16	87 ± 30.7	1.18	106.2 ± 37.2	1.38	97.6 ± 33.1	1.23	–	–	96.9 ± 33.7	1.12
	17-Jun-16	91.6 ± 18.2	1.12	**108.9 ± 37.5**	**1.54**	**109.7 ± 25.9**	**1.37**	–	–	103.4 ± 27.2	1.15
	12-Jul-16	80.7 ± 16.7	1.19	93 ± 48.6	1.74	**108.4 ± 26.3**	**1.63**	–	–	94 ± 30.5	1.24
	9-Aug-16	79.9 ± 22.1	1.35	**88.2 ± 52.7**	**1.91**	**101.5 ± 27.4**	**1.64**	–	–	89.9 ± 34.1	1.29
	9-Sep-16	**79.2 ± 20.4**	**1.51**	57.9 ± 31.7	1.26	**113 ± 28.7**	**2.10**	–	–	83.4 ± 26.9	1.52
	22-Oct-16	111.2 ± 36.8	1.17	95.6 ± 39.2	1.21	101.9 ± 32.9	1.18	**140.2 ± 18.3**	**1.40**	112.2 ± 31.8	1.19
	6-May-17	97.6 ± 42.6	0.83	128.2 ± 46.4	1.22	123.7 ± 22.5	1.14	170.2 ± 16.7	–	127.2 ± 27.2	1.08
20-60	19-May-17	121.2 ± 45.6	0.98	131.5 ± 42.3	1.09	123.3 ± 31.2	1.14	**151.2 ± 22.4**	**1.51**	130 ± 27.5	1.12
	6-Jun-17	78.8 ± 25.8	0.94	107.5 ± 44	1.28	**103 ± 19.4**	**1.24**	**133.8 ± 24.3**	**1.25**	99.8 ± 22.7	1.05
	24-Jun-17	105.7 ± 16.9	1.05	128 ± 39.2	1.29	**95.8 ± 30**	**1.30**	**158.2 ± 38.3**	**1.55**	115.1 ± 27.4	1.14
	12-Jul-17	63.1 ± 27.7	0.85	79.8 ± 54.5	1.49	**106.5 ± 32.8**	**1.48**	**121.3 ± 34.4**	**1.44**	91.3 ± 31.6	1.18
	25-Jul-17	53 ± 25.1	0.82	65.5 ± 62.3	1.35	**91.6 ± 30.3**	**1.39**	**107.3 ± 29.4**	**1.42**	79.2 ± 26.4	1.17
	7-Aug-17	45.4 ± 16.4	0.76	82.5 ± 60.3	1.60	**89.5 ± 34.3**	**1.51**	**113 ± 44.2**	**1.62**	76.8 ± 30.8	1.13
	24-Aug-17	44.9 ± 11.4	0.88	75.8 ± 54.7	1.48	**88.1 ± 36.7**	**1.50**	**111.4 ± 37.5**	**1.73**	73.8 ± 25.3	1.18
	28-Sep-17	57.4 ± 7.6	1.12	72.9 ± 43.5	1.57	**71.6 ± 31.9**	**1.62**	73.5 ± 21.7	1.04	63.4 ± 20	1.06
	21-Oct-17	66.7 ± 22.1	1.19	80 ± 46.6	1.41	**100.6 ± 27.9**	**1.37**	105.2 ± 33.8	1.32	82.2 ± 26.4	1.14
	Mean ± S.E.	79.8 ± 5.5	0.92	85.7 ± 6.2	1.24	101.9 ± 3.1	1.37	125.9 ± 6.8	1.19	95.7 ± 4.5	1.17

Table 3-4: Summary of spearman rank correlation coefficients 15 snow-free dates for all sites across all snow-free soil moisture survey dates. Coefficient values reflect temporal stability of soil moisture patterns within each site.

Depth (cm)		Clearcut N		Clearcut S		Strip-shelterwood		Partialcut		Mean All	
		Harvest	Reference	Harvest	Reference	Harvest	Reference	Harvest	Reference	Harvest	Reference
0-20	Mean	0.67	0.77	0.70	0.77	0.78	0.70	0.67	0.75	0.70	0.75
	Max	0.98	0.97	0.96	0.97	0.97	0.94	0.87	0.95	0.95	0.96
	Min	0.03	0.40	0.29	0.47	0.47	0.38	0.32	0.46	0.28	0.43
	CV	0.29	0.16	0.20	0.14	0.13	0.19	0.20	0.14	0.21	0.16
	% Signif	73	95	93	99	100	100	91	98	89	98
20-60	Mean	0.56	0.62	0.50	0.72	0.65	0.61	0.52	0.39	0.56	0.58
	Max	0.98	0.95	0.94	0.94	0.93	0.88	0.87	0.83	0.93	0.90
	Min	-0.23	-0.04	-0.24	0.44	0.29	0.37	-0.15	-0.32	-0.08	0.11
	CV	0.39	0.47	0.63	0.16	0.21	0.19	0.37	0.59	0.40	0.35
	% Signif	62	67	57	96	99	100	69	38	72	75

Table 3-5: Pearson correlations between environmental variables and SMS in harvested and corresponding reference sites (shown in brackets) across all survey dates. Mean coefficients relate to correspondence of each factor with mean SMS over all survey days. Values in bold are significant at α=0.05.

Depth (cm)	Variable	Clearcut N (Reference N)			Clearcut S (Reference S)			Strip-cut (Strip-forest)			Partialcut (Reference)			All
		Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean
0-20	Peak SWE 2016	-0.24 **(-0.86)**	-0.37 **(-0.93)**	0.01 (-0.19)	-0.02 (0.18)	0.20 (0.40)	-0.01 (-0.01)	-0.32 (0.02)	**-0.34** (0.33)	0.00 (-0.07)	– –	– –	– –	**0.29**
	Peak SWE 2017	0.12 (-0.30)	**0.63** (-0.51)	0.03 (0.01)	0.03 (-0.04)	0.43 (0.34)	0.00 (0.04)	0.17 (0.19)	**0.47** (0.28)	0.06 (-0.02)	0.17 **(0.57)**	**-0.87 (0.60)**	0.04 (0.34)	**0.25**
	Aspect	0.04 (0.06)	0.31 (0.26)	0.02 (-0.01)	-0.09 (0.46)	-0.49 **(0.60)**	0.00 (0.14)	0.11 (-0.21)	**0.33** (-0.30)	-0.06 (-0.03)	-0.11 **(0.53)**	-0.21 **(0.65)**	0.01 (0.33)	0.02
	Elevation	-0.30 **(-0.72)**	**-0.74 (-0.80)**	-0.11 (-0.50)	-0.10 (-0.33)	**-0.59 (-0.57)**	0.00 (-0.01)	0.27 (-0.06)	**0.62** (-0.2)	0.11 (0.00)	-0.18 (0.41)	-0.34 **(0.49)**	-0.01 (0.19)	**0.21**
	Slope	0.18 (0.01)	**-0.77 (-0.89)**	0.10 **(-0.61)**	0.04 (0.17)	0.53 (0.47)	0.00 (0.00)	**0.29** (0.08)	**-0.38** (-0.35)	-0.13 (0.00)	-0.23 **(-0.58)**	-0.35 **(-0.63)**	-0.03 (-0.28)	**-0.11**
	TWI	0.27 **(0.76)**	-0.51 **(0.80)**	0.04 (0.47)	0.11 (0.12)	**0.61** (0.29)	0.01 (0.03)	-0.01 (0.08)	-0.38 (0.26)	0.00 (0.01)	0.21 (0.09)	0.21 (-0.16)	0.01 (-0.03)	**-0.12**
	OM thickness (0-20)	0.15 (-0.27)	0.39 (-0.38)	0.05 (-0.11)	-0.05 (0.08)	-0.25 (0.25)	-0.01 (0.00)	**-0.37 (-0.46)**	**-0.50 (-0.64)**	-0.17 (0.08)	0.04 (-0.35)	-0.25 **(-0.54)**	-0.01 (-0.23)	**-0.09**
	Canopy Cover	– (-0.04)	– (-0.47)	– (0.04)	– (-0.30)	– (-0.49)	– (0.02)	0.01 (0.48)	0.27 **(0.57)**	-0.02 (0.05)	-0.18 (0.13)	**-0.87** (0.53)	0.18 (0.07)	**-0.24**
	Vegetation cover	0.53 **(0.55)**	**0.89 (0.78)**	0.08 (0.37)	-0.17 (0.04)	-0.49 (0.33)	-0.01 (0.00)	-0.16 **(0.53)**	**-0.41 (0.6)**	0.00 **(0.36)**	0.20 (0.43)	0.39 **(0.54)**	0.09 (0.23)	-0.01
20-60	Peak SWE 2016	0.37 (-0.26)	0.43 (0.47)	0.00 (-0.01)	-0.35 (-0.05)	-0.66 (-0.34)	-0.07 (-0.05)	0.13 (0.11)	0.30 **(0.63)**	0.07 (0.07)	– –	– –	– –	**0.23**
	Peak SWE 2017	0.16 (0.14)	0.41 (-0.36)	0.02 (0.00)	**-0.55** (-0.15)	**-0.66** (0.39)	-0.16 (-0.01)	0.11 (0.11)	0.17 **(0.43)**	-0.02 (0.03)	-0.14 (0.24)	0.35 **(0.46)**	0.01 (0.03)	**0.12**
	Aspect	-0.01 (0.27)	**0.77** (0.71)	-0.02 (0.07)	-0.30 (-0.23)	**-0.73 (-0.52)**	-0.04 (-0.04)	0.19 **(0.39)**	0.26 **(0.56)**	-0.02 (0.03)	-0.21 (0.37)	-0.39 (0.48)	-0.02 (0.03)	**-0.14**
	Elevation	-0.28 **(-0.83)**	**-0.70 (-0.92)**	0.02 (-0.24)	**0.65** (-0.1)	**0.77** (-0.33)	-0.14 (-0.02)	0.29 **(0.49)**	**0.45 (0.69)**	-0.04 (0.22)	-0.38 (0.14)	**-0.45** (0.36)	-0.04 (0.02)	**0.07**
	Slope	-0.03 **(-0.87)**	**-0.64 (-0.9)**	-0.04 (-0.23)	**-0.63** (-0.18)	**-0.76** (-0.44)	0.03 (0.03)	0.12 (-0.18)	0.39 **(-0.39)**	0.00 (0.01)	-0.02 (-0.17)	-0.45 **(-0.48)**	0.04 (0.01)	**-0.14**
	TWI	0.20 **(0.87)**	-0.48 **(0.96)**	-0.03 (0.26)	**0.59** (-0.04)	**0.72** (-0.27)	0.01 (0.00)	-0.03 **(-0.41)**	-0.30 **(-0.52)**	0.01 (-0.03)	0.31 (0.03)	0.44 (0.33)	0.04 (0.01)	**-0.04**
	OM thickness (0-20)	0.18 (-0.04)	-0.44 (-0.32)	0.02 (0.01)	0.32 (0.20)	0.42 (0.39)	0.02 (-0.03)	0.02 (0.01)	-0.32 **(-0.41)**	0.00 (0.00)	0.07 **(-0.50)**	0.37 **(-0.55)**	-0.05 (0.05)	**-0.06**
	OM thickness (0-60)	-0.43 (-0.14)	**-0.77** (-0.47)	-0.09 (0.01)	-0.23 (0.05)	-0.37 (0.42)	0.00 (-0.02)	-0.08 (-0.07)	-0.40 (-0.20)	0.01 (-0.01)	0.10 (-0.38)	0.64 **(-0.53)**	-0.02 (-0.04)	**-0.13**
	Canopy Cover	– (0.05)	– (0.45)	– (0.01)	– (0.21)	– (0.42)	– (-0.04)	0.34 (0.01)	-0.56 **(0.96)**	0.01 (-0.01)	-0.18 (0.14)	0.66 (-0.40)	0.11 (0.00)	**-0.15**
	Vegetation cover	-0.13 **(0.65)**	**-0.76 (0.74)**	0.00 (0.19)	**-0.59** (0.11)	**-0.67** (0.28)	0.04 (0.00)	-0.21 **(-0.35)**	-0.33 **(-0.45)**	-0.11 (0.01)	-0.17 **(0.51)**	-0.61 **(0.65)**	0.00 (-0.05)	**-0.08**

Table 3-6: Spearman's Rank Correlation values between patterns of soil water storage and cumulative radiation since last measurement in 2016 and 2017, in harvested strips and north and south facing clearcuts. Values in bold are significant based on α=0.05.

			Observation Date									
Site	Depth (cm)	Year	2	3	4	5	6	7	8	9	10	All
Strip-harvest	20	2016	-0.04	0.18	0.25	0.14	-0.05	-0.21	–	–	–	*0.017*
		2017	0.26	0.16	0.12	0.22	0.11	0.03	-0.07	-0.25	-0.19	
	20-60	2016	0.01	-0.20	-0.22	0.02	-0.08	0.11	–	–	–	*0.02*
		2017	-0.35	-0.18	-0.09	-0.15	0.05	0.09	0.10	0.13	-0.03	
North and South Clearcut	20	2016	-0.23	-0.29	-0.10	-0.06	-0.35	-0.07	–	–	–	***-0.1***
		2017	-0.13	-0.10	-0.16	-0.07	-0.06	-0.04	-0.02	-0.16	0.00	
	20-60	2016	**0.51**	0.35	0.28	0.15	**-0.48**	-0.08	–	–	–	0.06
		2017	0.11	0.30	**0.57**	0.12	-0.02	0.03	0.21	-0.04	-0.05	
All	20	2016	-0.16	**-0.29**	**-0.28**	**-0.27**	**-0.45**	**-0.26**	–	–	–	***-0.08***
		2017	0.02	-0.18	**-0.33**	-0.15	-0.02	-0.11	-0.22	-0.24	-0.26	
	20-60	2016	0.15	-0.10	**-0.24**	-0.12	**-0.44**	0.06	–	–	–	-0.02
		2017	-0.01	-0.15	**0.35**	**-0.35**	**-0.25**	**-0.28**	-0.12	-0.10	**-0.26**	

Figure 3-1: (A) Location of the study area in Star Creek watershed, in relation to the community of Coleman, Alberta. (B) Schematic map of harvesting treatments in the Star Creek watershed, as well as locations of soil moisture sampling transects, soil pits, and meteorological stations.

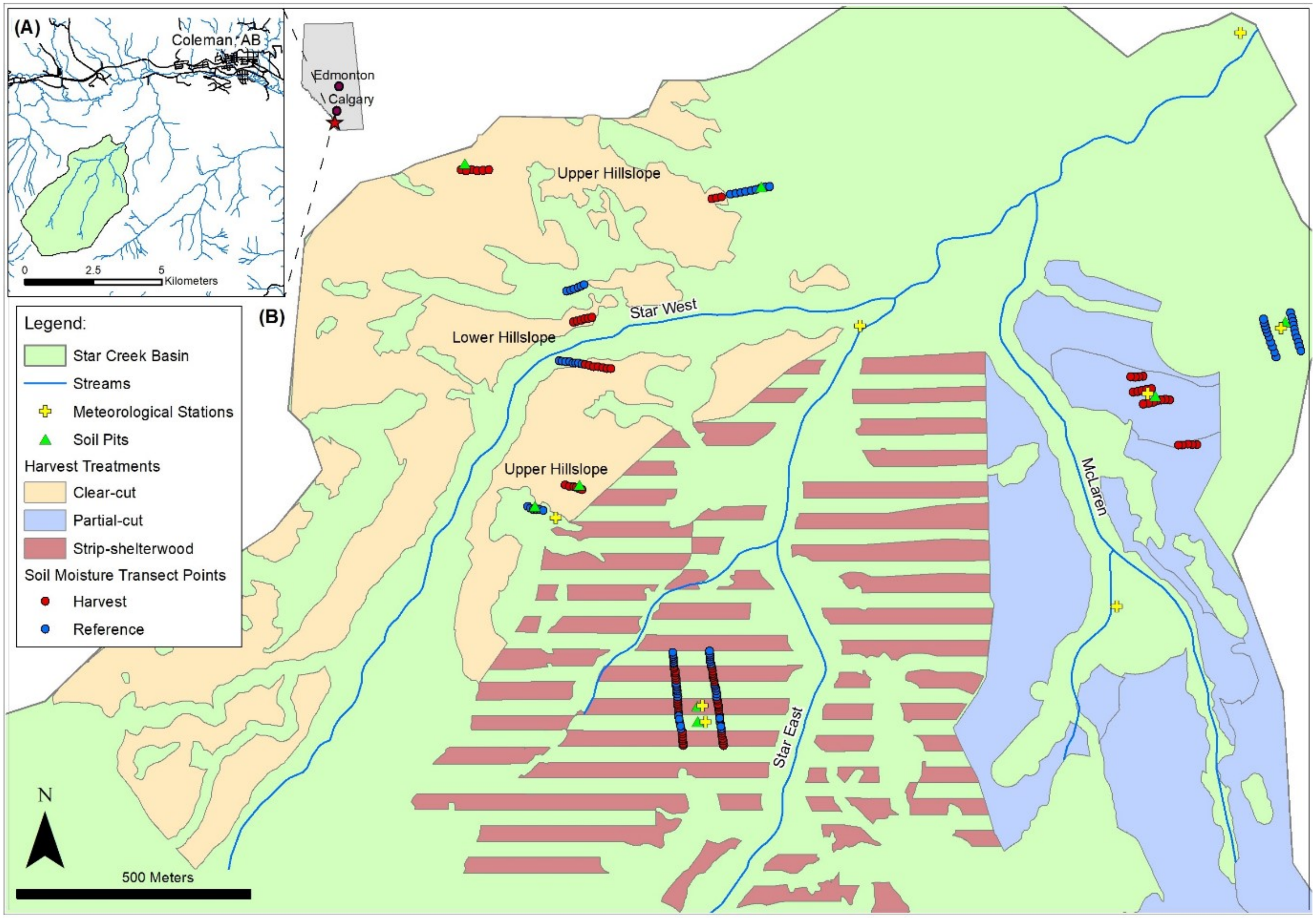


Figure 3-2: (A) Orthorectified satellite image of the harvest area in Star Creek; (B) LiDAR derived digital elevation model of the harvest area, where lighter colours denotes higher elevation; (C) Map of harvest area slope distributions; (D) Topographic wetness index.

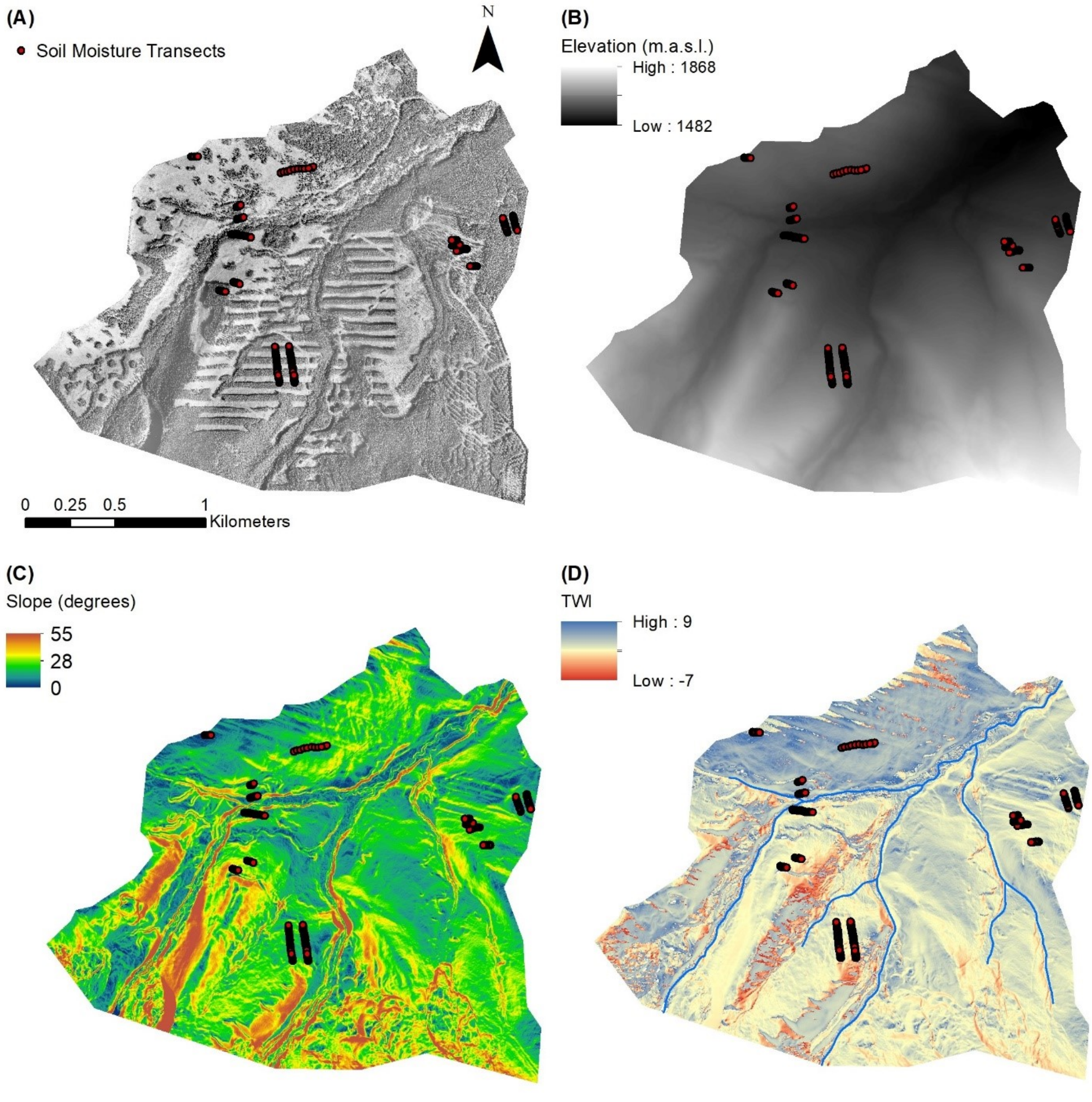


Figure 3-3: Temporal patterns of monthly precipitation and potential evapotranspiration in Star Creek during the study. Dashed grey rectangles denote duration of sampling within each year.

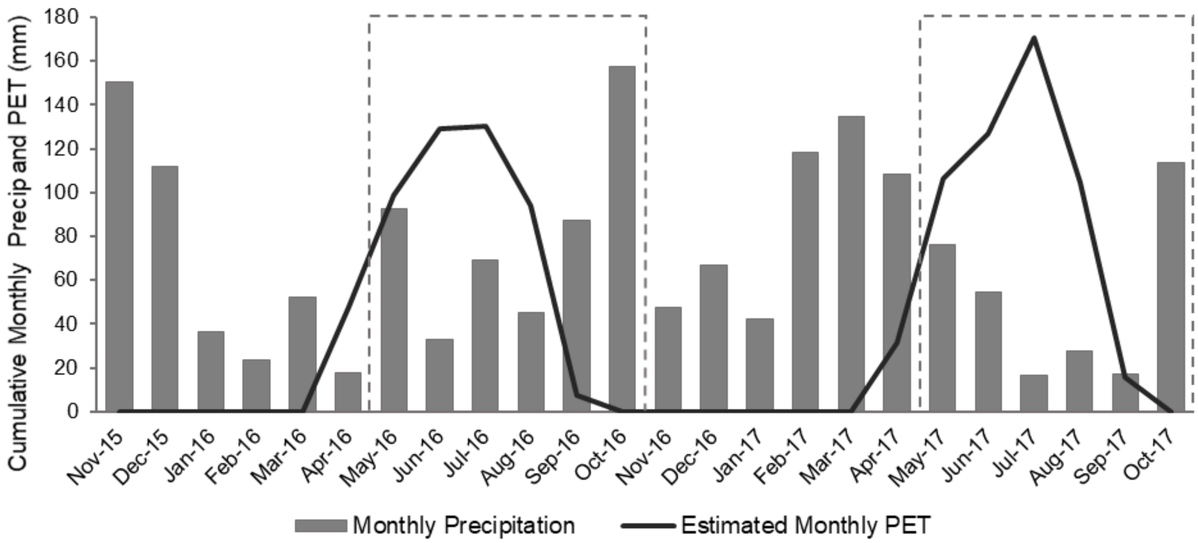


Figure 3-4: 2017 mean catchment air temperature, precipitation, and soil volumetric water content (VWC) measured continuously at 5 cm, 20 cm, and 60 cm depths, and from periodic surveys at 0-20 and 20-60 cm depth intervals.

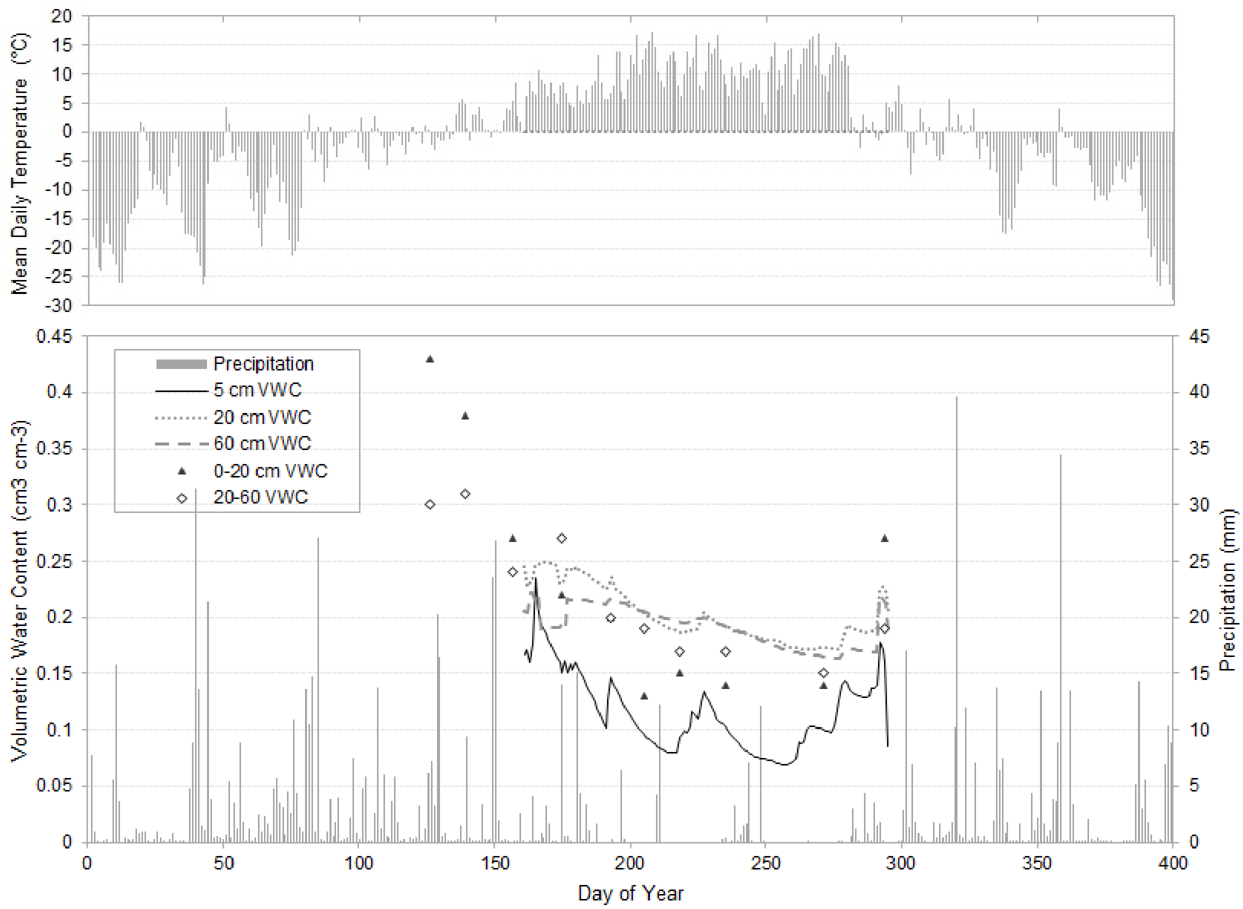


Figure 3-5: Mean SMS in 0-20 cm and 20-60 cm depth soil layers across repeated measurement from May to October of 2016 and 2017. Harvested sites are described by solid lines with triangular points, and corresponding forested reserves by dashed-lines and circles. Partial-cut and corresponding forest SMS were measured once in 2016 on Oct. 22 but not included, values are presented in Table 3-3.

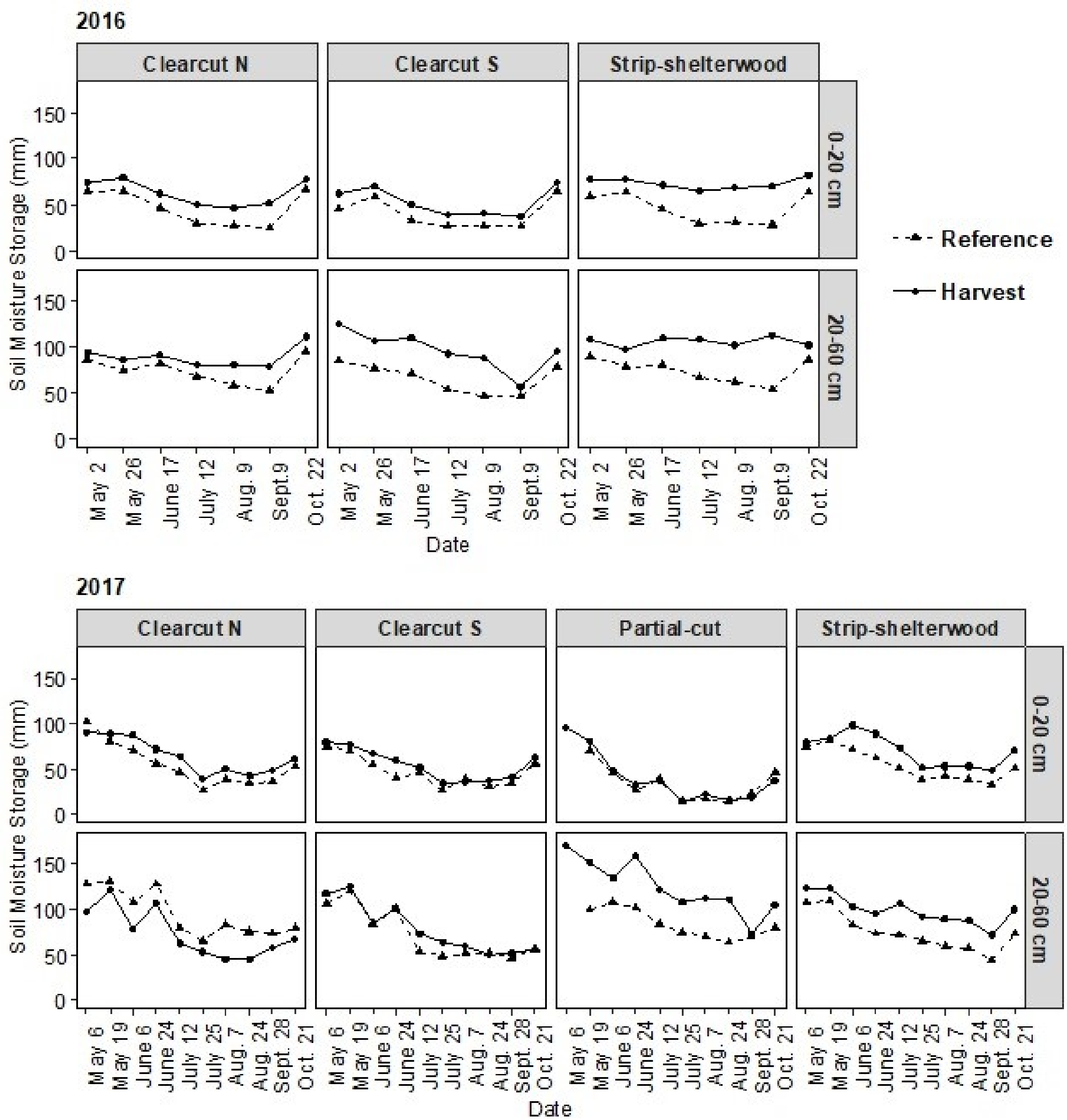


Figure 3-6: Mean relative differences between basin mean and harvest/control SMS across all sampling dates in (A) 0-20 cm and (B) 20-60 cm deep soil layers, where CC-N = clearcut north, CC-S = clearcut south, PC = partial cut, SS = strip-shelterwood. Horizontal dashed grey line denotes time stable position of basin mean SMS, with points and error bars describing mean relative difference in SMS and corresponding standard deviation for each harvest/reference.

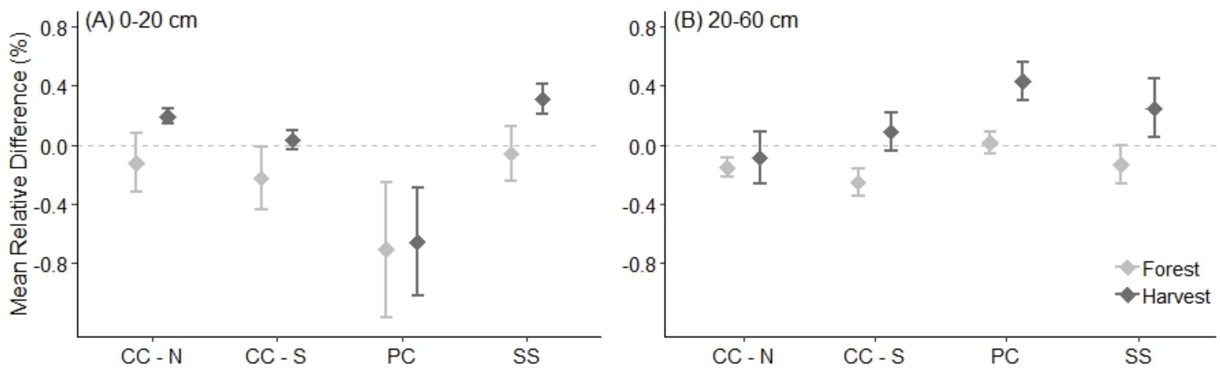
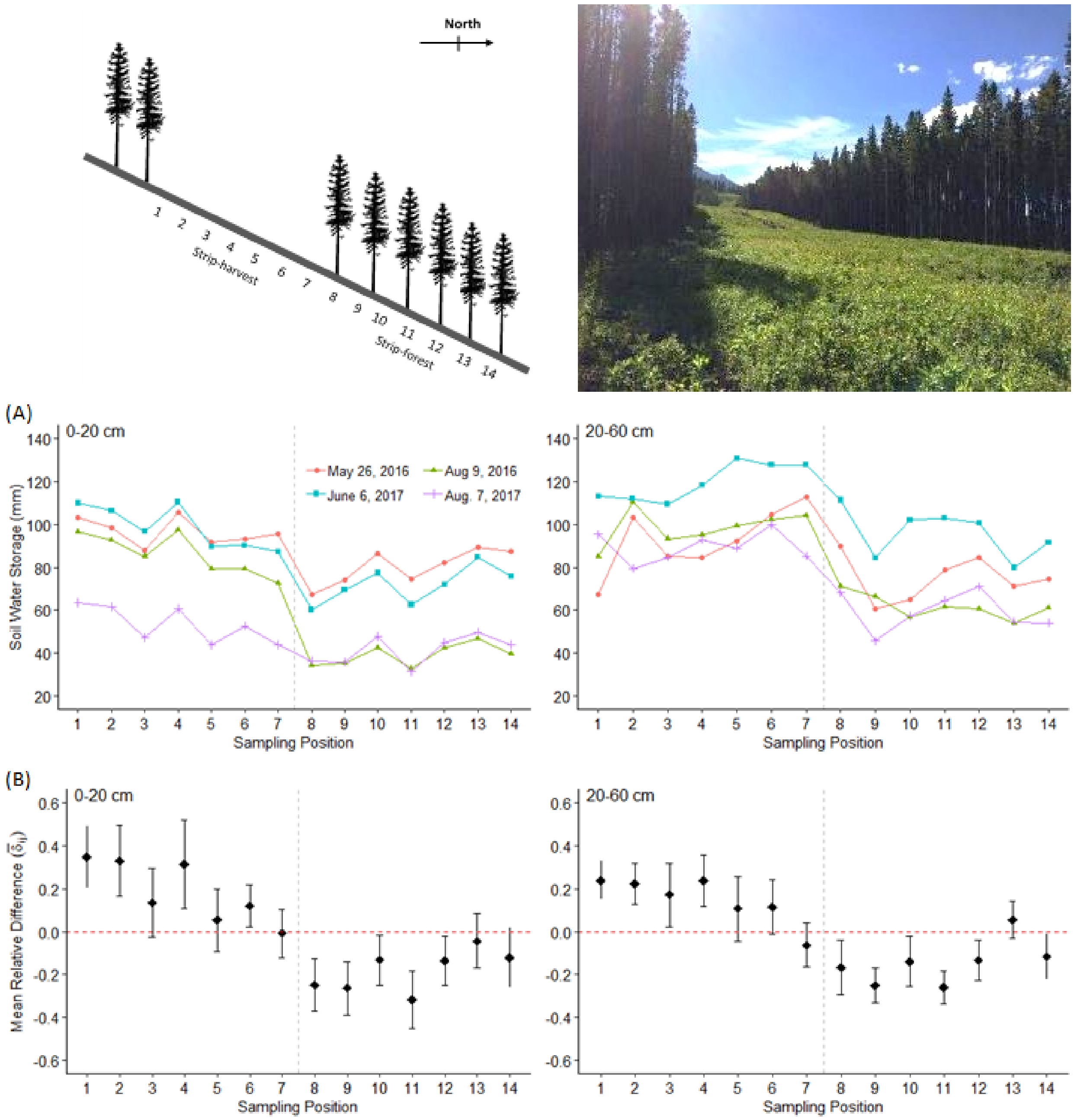


Figure 3-7: Upper: (Left side) Conceptual image of SS transect sampling point; and (Right side) Accompanying image of a harvested-strip. Lower: (A) Spatial distribution of soil moisture storage at each sampling position across the width of harvested and forested strips for four sampling occasions in 2016 and 2017. Vertical dashed line indicate transition between harvested and forested/shelterwood strips. (B) Mean relative differences between SMS at each position and the site mean, with corresponding standard deviation over all snow-free sampling dates described by error bars. Horizontal red line denotes time stabilized mean SMS across all sites and snow-free sampling dates.



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Chapter 4: Synthesis

Low-order forested catchments on the eastern slopes of the Canadian Rockies are a critical source of regional surface water supplies in southwestern Alberta. However, cumulative pressures from climate change and extensive land-disturbance by timber harvesting may impact these vital water resources because changes in climate and forest cover alter hydrologic processes including snowpack accumulation and melt, and seasonal soil moisture storage (SMS), that control runoff generation. While hydrologic effects from clearcut harvesting have been widely researched, comparative effects from alternative harvesting strategies that have potential to improve integrated forest-water management have remained less well understood. Accordingly, the primary goal of this study was to evaluate the effects of three specific alternative timber harvesting strategies (clearcut with retention [CC], strip-shelterwood [SS], and uniform partial-cutting [PC]) on snowpack accumulation and melt (Chapter 2), and soil moisture storage (SMS)(Chapter 3) dynamics.

Effects of harvesting using each of the three harvesting strategies on spatial and temporal patterns of snow accumulation and melt were evaluated in the context of their effects on microclimate and solar radiation from 2016 to 2018 in Chapter 2. Broad results from this study showed that all three harvesting strategies significantly affected snow accumulation and melt dynamics. However, effects differed widely between harvesting methods because specific spatial patterns of tree retention affected spatial patterns of canopy interception that controlled snow accumulation; and solar insolation and wind exposure that controlled snowpack losses.

CC harvesting resulted in either unchanged or significantly reduced snowpack accumulation because reduced interception losses were offset by similar or greater snow ablation losses from increased wind and solar radiation exposure. This result provided a notable contrast from previous research that has widely reported increases in peak SWE after clearcutting (Boon, 2012; Gelfan et al., 2004; Hubbart et al., 2007; Jost et al., 2007; Murray and Buttle, 2003; Schelker et al., 2013; Storck et al., 2002; Troendle and Reuss, 1997; Winkler et al., 2005). Findings from this study therefore highlight the importance of considering site-specific factors including climatic conditions such as wind, temporal pattern of snowfall, and winter air humidity that govern local snow processes when predicting or generalizing the effects of clearcutting on seasonal snowpack accumulation. PC harvesting resulted in a significant increase in peak SWE at the upper end of increases reported from similar previous studies (Alexander et al., 1985; Gary and Watkins, 1985; Troendle and King, 1987), but also increased exposure to radiation with minimal shading from spatially-dispersed residual trees allowing faster snowmelt that was synchronized with melt rates in undisturbed forests, similar to findings by Winkler et al. (2005). Among all three strategies, SS harvesting had the strongest effect on both accumulation and melt, increasing mean peak SWE in 2016-2018 by amounts similar or greater than those reported by past research (Gary, 1974; Leaf, 1975) because harvested strips both reduced interception while shading by forested-strips strongly reduced radiation-driven melt rates, resulting in both decreased snowpack losses and extended snowmelt duration.

Slope aspect was a critical factor that influenced snow accumulation and melt timing observed in this study. Repeated snow-course surveys in 2016 and 2017 showed the timing of snow disappearance occurred almost two weeks earlier in south-facing CCs than in north-facing CCs and undisturbed forests on both north- and south-facing slopes. South-facing slope aspect and clearcutting each increase shortwave radiation exposure, which collectively increase rates of snowpack ablation over that of adjacent forests and opposite north-facing slopes (Jost et al., 2007; Murray and Buttle, 2003; Packer, 1971; Pomeroy et al., 2003; Winkler et al., 2005). Results from the SS harvest demonstrated how interactions between topographic shading provided by northerly hillslope aspect and shading from E-W oriented shelterwood strips also minimized radiation to significantly increase post-harvest snow accumulation and melt duration. While topographic shading has been shown to have a greater effect on snowmelt during earlier spring warming, because lower solar angles result in larger differences in net radiation received by shaded versus unshaded areas (Lundquist and Flint, 2006), relative differences in snowpack accumulation measured in 2016 and 2017 suggest this relationship may include shading also provided by residual trees, and that this has a greater effect on snowpack ablation during warmer winters.

While the influence of forest cover on snowpack dynamics has been well described, findings from this study provide new information by quantifying the comparative effects of CC, SS, and PC harvesting on snow accumulation and melt dynamics in the context of interactions between spatial patterns of tree retention and prevailing climate and topographic controls. These results strongly supported my initial hypothesis that alternative harvesting strategies would result in differing patterns of snow accumulation and melt because of the influence of harvest-cutting patterns on microclimate and solar radiation forcing. Overall results from Chapter 2 strongly reinforce the importance of radiation as moderator of snow accumulation and melt, and also provide fundamentally new insights on the comparative effects of different harvesting practices because few previous studies have evaluated these concurrently. This comparative evaluation clearly highlights the need to collectively consider patterns of tree retention together with slope orientation when evaluating how forest harvesting may affect the rate, timing, and synchronization of catchment snowmelt, for example through physically-based predictive models.

The second data chapter (Chapter 3) reported on parallel comparative effects from timber harvesting on spatial and temporal patterns of seasonal soil moisture. Effects from each of the three harvesting strategies on spatial and temporal patterns of seasonal SMS were evaluated in the context of microclimate, radiation forcing, and a range of other key environmental factors using extensive field data collected from harvested and forest reference sites during snow-free seasons in 2016 and 2017. Results presented in Chapter 3 showed that similar to patterns observed for snow accumulation and melt, harvesting strategies had a significant effect on seasonal SMS which differed strongly between harvest types. Spatial and temporal patterns of SMS differed among alternative harvesting strategies because spatial patterns of tree retention produced corresponding spatial differences in seasonal soil-water balance; from water input by snowmelt and rain throughfall; and water loss through tree-transpiration and turbulent vapour exchange.

CC harvesting resulted in variable but significant increases in SMS at both 0-20 and 20-60cm depths during periods of higher moisture availability in 2016 that were generally similar but comparatively moderate to those reported in past research (Adams et al., 1991; Bethlahmy, 1962; Dhakal and Sidle, 2004; Megahan, 1983; Redding et al., 2003; Chin, 2009). However, relative differences in SMS between CC and forested sites were reduced during drought conditions in 2017. PC harvesting also resulted in significantly increased SMS, but only in deeper 20-60cm soil layers in 2017. SS harvesting again, had the largest and most stable effects on SMS with harvested strips maintaining significantly elevated surface (0-20cm) and subsurface (20-60cm) seasonal SMS over respective wet and dry study years. Relative differences in SMS over respective wet-and dry study years suggest that tree removal likely drives decreased net water losses (precipitation interception, transpiration). Results also showed these effects may be more susceptible to climatic influence in CC and uniform PC harvested sites because absent or spatially-dispersed residual trees do little to moderate wind and solar radiation exposure that drive surface soil moisture losses via evaporation. Conversely, highly consistent differences in SS SMS demonstrated that SS harvesting on north-facing slopes may reduce soil-atmospheric water losses even under strongly variable seasonal and inter-annual climates conditions because of strong microclimate and radiation forcing.

Analyses of snowpack dynamics in Chapter 2 showed that shading associated with slope-aspect and the width and orientation of forested-strips created spatial patterns of snowpack accumulation and melt broadly analogous to those observed for SMS in 0-20 cm soil layers. Correspondence between spatial patterns of snow accumulation and melt and SMS may reflect the importance of winter snowmelt legacy on seasonal soil moisture but also likely indicate their parallel control by the same key factors. While several past studies that have demonstrated strong spatial coupling between forest cover and snow and soil moisture dynamics (Conner et al., 2016; Ebel et al., 2012; Kampf et al., 2015; Smith, 2011), no previous studies (to-my-knowledge) have assessed this relationship across multiple timber harvesting methods at the same time. Comprehensive results from this study provide new insight by highlighting how specific forest harvesting strategies influence these interactions. While weak correlation between solar radiation and SMS in this study contrast with previous findings (Redding et al., 2003) and closer correlation with snowpack dynamics in Chapter 2, this is likely because radiation modeling approaches used by this study did not incorporate radiation transmission through retained tree canopies, which is likely to have a stronger effect on spatially varied solar insolation during summer when solar angles are high and topographic shading is reduced. Further research would help more accurately quantify these solar radiation dynamics. Nonetheless, collective results from this analysis provide new information beyond the scope of currently published work directly quantifying comparative differences in the influence of alternative harvesting strategies on seasonal SMS. Results here emphasise the need for hydrologic modeling to incorporate detailed consideration of stand-scale interactions between forest canopy cover and solar-energy balance when evaluating the spatial linkages between snowpack and soil moisture storage dynamics.

Comprehensive results from this study clearly demonstrate how interactions between specific patterns of tree retention used by alternative harvesting methods, together with slope-orientation may moderate broader seasonal climate/meteorological forcing and corresponding spatiotemporal water balance dynamics that regulate runoff from forested mountain watersheds in this critical water supply region. Moreover, distinct differences measured between how respective harvesting methods influenced snowpack accumulation and melt and SMS over contrasting water years provide new insight into how alternative strategies are likely to affect snowpack and seasonal SMS dynamics in the context of climate change. These overall results provide much needed information that lays the groundwork for continued research aimed at improving integrated forest-water management in this vital water supply region

4.1 Future research

Differing spatial and temporal patterns of snow accumulation and melt and SMS observed in this study are important predictors of how alternative forest harvesting strategies are likely to influence catchment runoff dynamics and forest regeneration under differing climatic conditions, however continued research is needed to address outstanding knowledge gaps. While numerous previous studies have demonstrated changes in catchment water yield from forest harvesting (Bosch and Hewlett, 1982; Brown et al., 2005; Hubbart et al., 2007; Stednick, 1996) results remain highly varied across methods and settings where each were conducted. Past research has shown changes in catchment water yield and streamflow behaviour are highly dependent on the extent of forest harvesting (i.e. percent of land or basal area harvested)(Brown et al., 2005; Green and Alila, 2012; Hubbart et al., 2007; Stednick, 1996). Moreover, effects from harvesting on snowpack and SMS dynamics typically diminish over time due to forest regeneration and hydrologic recovery (Adams et al., 1991; Hornbeck et al., 1993), although impacts on water yield have been detected up to 30 years after harvest (Troendle and King, 1985). Further research is needed to evaluate the magnitude and duration of observed effects from forest alternative harvesting strategies. This includes an assessment of scales at which these effects may meaningfully influence regional water supply values, and the duration that these effects persist in consideration of hydrologic resilience and post-harvest recovery. Continued research that directly quantifies the comparative effects of each of these alternative harvesting strategies on runoff generation, including hydrograph variance and peak, and total annual discharge, is critical to evaluate the potential efficacy of these strategies for integrated forest-water management for long-term climate change adaptation. Along with results from this study, these data are vital for testing and validating physically-based models that allow these stand- and watershed-level effects can be extrapolated to the regional basin scales at which resource-planning and policy decisions are made.

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Appendix A: Clockwise from upper left: clear-cut (CC); strip-shelterwood (SS); partial-cut (PC); example of snowpack and SMS sampling transects as seen in the CC