SNOW DYNAMICS AND SOIL MOISTURE

IN COMMERCIALLY THINNED LODGEPOLE PINE SILVOPASTURES

ON THE OKANAGAN PLATEAU OF SOUTHERN BRITISH COLUMBIA

By

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Thompson Rivers University, 2023

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTERS OF SCIENCE in ENVIRONMENTAL SCIENCE

in the Faculty of Science

THOMPSON RIVERS UNIVERSITY

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ABSTRACT

Forest harvesting systems may be strategically designed to manipulate snow accumulation and soil moisture, not only to improve forage and timber productivity, but also to improve flood, wildfire and climate change mitigation. The objectives of this study were to investigate differences in snow accumulation, snow ablation, and soil moisture across various widths of commercial strip-thinning in silvopasture systems. Silvopastures were established near Kelowna, British Columbia, Canada. Stands of 45-year-old *Pinus contorta* (lodgepole pine) were commercially thinned in the summer of 2018. Strip-harvest treatments were linear and of various widths: 10 m, 15 m, and 20 m. Treatments were allocated in a two-factor randomized block design; strip width and orientation. Adjacent forested areas and a clearcut were also examined as controls. Strips were harvested with either east-west, or north-south orientations. Snow water equivalent was manually sampled during winters of 2019-2020. From May 2019 to October 2020, volumetric water content was continuously sampled at two depths (0-10 cm and 25 cm below the soil surface) and soil temperature was continuously measured at 5 cm depth. Snow accumulation increased with strip-width, and 20 m strips retained a mean peak accumulation of SWE which was 11.4 % greater than the clearcut ($P=0.001$). Snow accumulation and ablation-rates were directly associated with canopy cover and estimated solar radiation. The widest 20 m strips maintained greater soil moisture and soil temperatures throughout the growing season, compared to the narrower 10 m strips ($P<0.001$). However, 10 m strips did retain more soil moisture during drier months with limited precipitation ($P<0.001$), and strips orientated east-west retained the most soil moisture. Soil temperature was greater in both 10 m and 20 m strips compared to forested areas. This resulted in greater cumulative growing degree days (GDD) above the critical threshold of 5 °C in strips relative to non-harvested areas. Overall, strip-thinning and orientation of strips directly influenced snow accumulation, ablation dynamics, soil moisture, and temperature.

Keywords: agroforestry, silvopasture, strip, thin, snow, soil moisture

ACKNOWLEDGEMENTS

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Beef Cattle Research Council

Special thanks to:

Colleagues and the Fraser Lab at TRU

Trevor Blenner-Hassett, Ph.D., Forestec Forestry Consulting

John Church, Ph.D., Associate Professor, TRU

Rita Winkler, Ph.D., RPF, BC MoFLRNOR

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AAC: Annual allowable cut

AUM: Animal unit month

BEC: Biogeoclimatic (ie. Biogeoclimatic Zone)

FC: Field capacity

GDD: Growing degree days

IFM: Intensive forest management

LLWR: Least-limiting water range

MS: Montane Spruce (ie. Montane Spruce Biogeoclimatic Zone)

PWP: Permanent wilting point

SOM: Soil organic matter

SWE: Snow water equivalent

TSA: Timber supply area

UWR: Ungulated winter range

VWC: Volumetric water content

1.0 CHAPTER 1 – GENERAL INTRODUCTION

1.1 SILVOPASTURE

The first assumption in the discussion of strategic forest and range planning is that sustainability is a universal objective. The concept of sustainable forest practices can be defined from three perspective pillars: environmental, social, and economical (Hansmann et al. 2012). Sustainable resource management involves the improvement of environmental stewardship, in combination with long-term promotion of socio-economic values (Mann et al. 2018). Maintenance of economies, cultures, and quality of life constitute the socio-economic pillars (Purvis et al. 2019). However, the long-term availability of resources for future generations, such as timber and rangeland, depend on all three conceptual pillars of sustainability. Only with the promotion of healthy and resilient ecosystems, can we maintain the longevity of our land and resources. Beyond the resources for immediate sale, are the resources and ecological processes on which life and productivity depend on, including: climate, habitat, soil, water, sunlight, and nutrients. Forest management strategies are becoming increasingly complex as the number of land-uses continue to increase and management objectives evolve (Fox 2000). In order to remain effective, successful forest practices and policies are required to adapt more quickly than the rate of climate change and must also adapt more quickly than the decline of available resources (Hannah et al. 2015). Integrated resource management strategies, such as silvopastures, have the potential to satisfy some of these objectives.

Mixed approaches, incorporating both fine and coarse-scale strategies, can help satisfy the wide range of integrated objectives involved in sustainable forest management. Agroforestry is one form of integrated resource management that has the potential to help satisfy multiple levels of objectives, from site-level to watershed scales (Anderson et al. 2008; Udawatta et al. 2011). Silvopasture, and other intensive forms of forest management, may help optimize the use of resources, such as water, sunlight, and soil nutrients (Rodriguez-Rigueiro et al. 2021).

Silvopasture is an agroforestry system designed to integrate timber, forage, and livestock production on the same land base (Bhardwaj et al. 2018). There are several forms of silvopasture used in temperate climates (Jose et al. 2019). Selections of suitable systems are primarily dependent on climate, vegetation communities, crop choice, natural disturbance regimes, and management objectives. In British Columbia (B.C.), Canada, silvopasture systems on provincial tenure should be selected for benefits which meet several criteria (**Table 1**).

Table 1. *A summary of proposed criteria for selection of successful agroforestry systems on Crown land in British Columbia, Canada.*

Criteria	References
Enhance environmental stewardship with sustainable resource management.	(Jose 2009; Elevitch et al. 2018)
Satisfy, or exceed, objectives of the *Forest Act* and *Forest and Range Practices Act.*	(Forest Act 1996; FRPA 2004)
Optimize value(s) of land use, such as forage availability and merchantable timber volume.	(Sharrow et al. 2009)
Contribute to carbon sequestration and climate change mitigation.	(Kim et al. 2016)
Promote resiliency to climate change and ecological disturbances	(Nitschke and Innes 2008)
Align with ecosystem restoration and wildfire risk reduction objectives	(Rodriguez-Rigueiro et al. 2021)

Demand for alternative forest harvesting methods is at an all-time high in Canada and is increasing globally (Fox 2000; Puettmann et al. 2015; Halofsky et al. 2018). Availability of first-growth timber supply is expected to decline before reliance will shift entirely onto replanted stands (BC Government 2019). Extensive harvesting, failed silviculture systems, climate change, insect damage, fungal pathogens, and wildfires have severely reduced timber supply in the interior of B.C. (Kurz et al. 2008; Alfaro et al. 2015; BC Government 2018, 2019). The amount of timber being hauled out of B.C forests has been declining since 2006, as beetle-killed salvage logging has declined. Most timber supply areas (TSA) are currently experiencing major decreases in annual allowable cut (AAC). Forecasts have projected declining trends in AAC, well into the future (BC Government 2019).

In B.C., the forest industry is highly dependent on public resources and unceded territory, which come with inherent costs of environmental stewardship. A shift to more intensive forest management may be one solution to a number of challenges arising in the industry. Intensive forest management strategies, such as thinning, pruning and fertilization, are designed to increase timber productivity while simultaneously satisfying additional land-use objectives, such as water and soil conservation (Fox 2000; Insley et al. 2002; Sing et al. 2018; Augustynczik et al. 2019). Economists are advocating for the development of more sustainable, investment-based industries (Insley et al. 2002; BCBC 2009; Baumgartner 2019; Sotirov et al. 2019). There has been an increasing number of incentives for intensive forest management, as timber supplies are diminished and the cost of lumber has reached unprecedented prices.

Forestry and cattle ranching have been two major industries both utilizing forested Crown land in B.C. for over a century. Cattle ranching has been a critical industry in B.C. since 1846 (McLean 1972). B.C.'s timber industry contributes approximately 19.6 % of the provincial GDP, or $12.94 billion (BC Council of Forest Industries 2016). Whereas, B.C.'s beef cattle industry contributes roughly 0.25 % of the provincial GDP, or up to $600 million annually (BC Cattlemen Association 2021). Strategic intensive forest management strategies have been shown to integrate these two industries on the same land base, increasing productivity and yield of both resources (Lindgren et al. 2017). There is a global push for optimization of multiple values on the land base and diversification of economies (Jose et al. 2019). Integrated land uses can promote cooperative stewardship and provide alternative strategies for managing ecological disturbances and effects of climate change (Mosquera-Losada et al. 2018).

Silvopasture systems have been globally recognized as a successful strategy to increase productivity and yield of trees, crops, and livestock (Verma et al. 2017). Some systems have been observed to increase timber quality, while simultaneously benefitting the beef cattle industry, sustaining additional economies, and providing interim cash-flow between timber harvests (Klopfenstein et al. 1997). Silvopastures also have the potential to be more environmentally ethical and sustainable, therefore more socially acceptable than conventional practices, such as: high-grading, large clearcuts, or slash-and-burn agriculture (Torralba et al. 2016; Jose et al. 2019).

Numerous environmental benefits have been observed in silvopasture systems compared to conventional practices alone (Pent 2020). Forests are globally recognized as successful carbon-sinks, estimated to sequester about 30 % of global annual carbon emissions (Hoberg et al. 2016). The majority of carbon sequestered by trees is stored above ground; whereas, the majority of carbon in grasslands is stored in roots belowground (Nilsson and Schopfhauser 1995; Soussana et al. 2006). Strategic agroforestry systems, with progressive management, have the potential to sequester more carbon both above and belowground and improve soil carbon processes (Sharrow and Ismail 2004; Nair et al. 2009; Pent 2020). The integration of silviculture and agriculture has the potential to provide synergistic benefits, which neither practice can provide alone.

Successful agroforestry systems are designed to optimize the use of environmental resources, such as: water, nutrients, and solar radiation (Yunusa et al. 1995). The optimal use of resources on any given site results in less nutrient loss from the land and more efficient use of available water (Boyer and Neel; Michel et al. 2007; Pent 2020). Tree cover naturally provides ecosystems some resiliency to climatic extremes, while also providing shelter and shade for livestock (Orefice et al. 2017). Silvopastures can also be designed to promote biodiversity, which indirectly improves ecological resiliency and resistance to climatic, pathogenic anomalies, or insect infestations (Lawrence et al. 1992; Jose et al. 2019). Seeding of multiple agronomic species, in combination with optimal grazing strategies, has been observed to improve the accumulation of soil carbon by increasing understory biomass, increasing biodiversity, and increasing root production (Frank et al. 1995). Strategic range management and rotational grazing plans, can improve forage productivity, improve plant regrowth after grazing, and improve soil organic carbon (Sanderman et al. 2015). Therefore, silvopastures have the potential to facilitate improved soil development, compared to conventional forest harvesting methods (Alemu et al. 2019). When coupled with greater productivity and economic yield, the environmental sustainability of silvopasture systems makes these practices more socially acceptable (Pent 2020).

Provincial *Forest Planning and Practices Regulations* hold licensees accountable for the conservation of site productivity and long-term sustainability (FRPA 2004). Silviculture practices have evolved over time to increase site productivity, which have involved trials and implementation of slash burning, thinning, pruning, fertilization, and pre-planting site preparation (BC Government 2003). Pre-commercial thinning involves the removal of young non-merchantable timber. Whereas, commercial thinning removes merchantable timber that has value associated with it and can therefore be sold to recuperate costs of the thinning treatment. Both types of thinning have been shown to increase overstory and understory productivity with accelerated succession in forest regeneration (Sullivan and Sullivan 2016). Increased herbaceous cover has been observed up to 25 years post-thinning, increasing the availability of natural forage for both cattle and wildlife (Sullivan and Sullivan 2016; Lindgren et al. 2017). Commercial thinning of mid-rotation trees with interim grass-seeding and livestock grazing has been trialed in this study as an agroforestry pilot project. Silvopastures have the potential to achieve multiple land-use objectives, while progressing the norms of sustainable forest management.

1.2 RANGE & LIVESTOCK

Rangeland includes all non-cultivated land that produces natural forage for wildlife and livestock (Campbell and Bawtree 1998). Forested range is the largest range type in B.C., which accounts for 90 % of all rangeland in the province (BC Government 1996). The remaining 10 % is divided between grasslands, meadows, wetlands, riparian zones, and alpine areas. Forage productivity across all rangeland is primarily determined by climates, soils, and vegetation communities.

In B.C., the Montane Spruce (MS) biogeoclimatic zones range from 1000 to 1700 m in elevation (Hope at al. 1991). These areas receive mean annual precipitation of 380 to 900 mm (Hope et al. 1991). Depending on the timing of snow disappearance, green-up and elevational gradients, these zones provide critical summer range for livestock from June to September (Wikeem et al. 1993). *Calamagrostis rubescens* (Pinegrass) often dominates the understory, which is a less desirable forage for ungulates and livestock (McLean 1967; Willms et al. 1980; Wikeem et al. 1993; Powell et al. 1994). Pinegrass is a source of nutrients and crude protein for cattle in early summer, but quickly loses nutritive value becoming unpalatable by mid-late summer (McLean 1967; Willms et al. 1980). Harvested forests can be seeded with agronomic mixes of higher nutritive content, including species such as, orchard grass (*Dactylis glomerata L.*), white clover (*Trifolium hybridum*), and wheatgrasses (Wikeem et al. 1993). In harvested openings, agronomic seeding has been overserved to produce 70 % more forage than unseeded areas (Wikeem et al. 1993). This not only contributes to increased animal unit months (AUM), the provincial standard in quantifying livestock forage, but increased yield of palatable grasses also helps maintain abundance and continuity of essential wildlife habitats (Nitschke and Innes 2008).

Alternative timber harvesting methods integrated with range management, as silvopasture, may provide opportunities of redesigning landscapes and vegetation to help achieve provincial objectives of biodiversity, carbon sequestration, productivity, and water management. Modification of tree cover in strips of different widths and orientations is expected to influence the snowpack, snow disappearance, timing of vegetative growth, and available moisture on the site. Such integrated management strategies have the potential to optimize productivity, by optimizing efficient use of resources, such as water, sunlight, and soil nutrients.

1.3 TIMBER

Lodgepole pine (*Pinus contorta*) has been relied on as a primary species for replanting harvested sites since the 1960s (Wu et al. 2005). However, the province of B.C. has experienced four massive outbreaks of mountain pine beetle (*Dendroctonus ponderosae*) in the last century (Taylor and Carroll 2003). Planting of lodgepole seedlings was substantially increased in the 1990's, as there was a provincial shift in silviculture practices that encouraged the reliance on planting of lodgepole pine due to the species hardiness and quick growth (Johnstone and van Thienen 2011). Nearly one billion lodgepole pine seedlings were planted in B.C., between 1999 to 2008 (Johnstone and van Thienen 2011).

Mountain pine beetle epidemics have been partially attributed to warming winter temperatures and the lack of extreme cold, which can naturally limit bark beetle populations. Mountain pine beetle prefers to attack mature trees, typically over the age of 40 years old (Amman et al. 1988; Amman and Logan 1998). Stressed trees, due to drought or nutrient deficiencies, are more susceptible to attack (Waring and Pitman 1983). There have been substantial efforts to harvest mid-rotation pine stands as they reach that age of susceptibility or recent beetle attack; this is known as one type of salvage logging that occurs within the province (FBP 2020).

Salvage logging with regards to bark beetles is often socially accepted; however, there has been a trend of licensees harvesting younger trees across the province regardless of species (Burton 2010). Younger stands are being harvested more frequently due to reduced timber supply and increased demand. Between 2007 and 2014, 24 % of all harvested timber did not satisfy minimum harvest criteria within the coastal timber supply area (FPB 2018). Minimum harvest criteria (MHC) outline conditions that must be satisfied prior to timber being harvested (FPB 2018). These criteria recommend minimum age, volume, or diameter in each timber supply area (TSA). These criteria prevent the harvest of young stands below culmination age, or below the age of maximum sustainable yield. Mid-rotation harvests are occurring more frequently as large diameter timber becomes less accessible and smaller diameter timber increases in value. Practices of harvesting young timber require alternative management strategies to maintain sustainable long-term timber supply (FPB 2018). Existing stands are also continually threatened by environmental and ecological disturbances, such as climate change, insects, and wildfires.

Climate change has been observed to be a major driver of fungal pathogen and insect outbreaks (Carroll et al. 2003; Whitehead et al. 2004). In B.C., lodgepole pine forests are experiencing the greatest environmental threats to their range of distribution relative to other conifer species (Mathys et al. 2018). Lodgepole pine is widely distributed with a broad fundamental niche, but increasing temperatures are providing favourable conditions for more competitive species, insects, diseases, and wildfires (Mathys et al. 2018; Stevens-Rumann et al. 2018). Besides bark beetle infestations, lodgepole pine stands are also susceptible to Western gull rust (*Endocronartium harknessii*), terminal weevil (*Pissodes terminalis*), and needle cast (*Cyclaneusma*), which can severely reduce merchantable timber volumes (Wu et al. 2005). Pre-commercial thinning and pruning of young lodgepole pine (<20 years old) has been shown to limit outbreaks of the fungal pathogen *Dothistroma* needle blight (*Dothistroma septosporum*) (Whitehead et al. 2004). Commercial thinning has repeatedly been shown to be effective at limiting the spread of these outbreaks, while promoting resistance and resiliency of the stand through changes in microclimate (Whitehead et al. 2004).

Lodgepole pine planted on drier sites are most susceptible to drought stress, disease, and mortality (FBP 2020). A report conducted by the Forest Practices Board (FBP) between 2007-2017, found that 60 % of all cutblocks harvested in the Interior Douglas-fir biogeoclimatic zone (IDF), were in “poor and marginal condition” (FBP 2020). The IDF zone has been projected to increase in size by 91 % by the end of the century, as historically wetter regions are anticipated to become drier (FBP 2020). Effects of climate change have been observable within single silviculture rotation periods (80-100 years), or in other words within the lifetime of a harvestable tree. Proactive forest management strategies are anticipating these rapid changes in climate (Aitken et al. 2008; Halofsky et al. 2018; Mathys et al. 2018; Sáenz-Romero et al. 2020).

Forest thinning is one strategy being implemented to improve ecological resiliency to climate change on drier sites (Wang et al. 2019). Thinning of lodgepole pine stands reduces competition for resources, such as light, nutrients, and water (Wang et al. 2019). Thinning also increases the width and length of crowns, as the trees take advantage of available light (Dahms 1971). The increase in radiation to the understory allows seedlings to grow faster in warmer soils (Balisky and Burton 1995). However, spacing lodgepole pine too widely can increase branch growth, thus reducing the quality of merchantable timber (Johnstone and van Thienen 2011). The excessive planting of lodgepole pine, in combination with poor stand health and management, have resulted in many cases of non-merchantable regenerated stands. Thus, strategic thinning and interim-silvopasture may be one solution in mitigating the provinces lodgepole pine situation, while simultaneously helping to achieve other objectives.

In the past, the primary objective of forest management has been the optimization of merchantable timber (Bell et al. 2008). The large area of public forests in Canada led to the development of large management units and an ‘extensive’ forest management approach. This strategy focuses on the basic requirements of stand regeneration, with focus on species composition and age-class. Large-scale, extensive management also facilitates additional landscape-level objectives pertaining to wildfires and insect mitigation (Bell et al. 2008).

On the other end of the spectrum, ‘intensive’ forest management (IFM) involves increased investment in silvicultural intensity at the site-level (Bell et al. 2008). IFM aims to improve stand yields, wood quality, and timber value, all while quickening the times for successful rotations. Globally, IFM has been popular in countries where forestry operations occur more often on private land with smaller management areas. Intensive silvicultural practices include: planning, site preparation, thinning, pruning, fertilization, species selection, and any variation of these interventions which produce faster and greater yield. On public lands, intensive forest management can adhere to higher-level plans and strategies facilitating an approach of integrated resource management. In best practice, all plans and operations on individual sites strive to satisfy all overlaying management objectives. Some examples include: watershed conservation, livestock forage, wildlife habitat, recreational value, and fire mitigation.

1.4 RESEARCH QUESTIONS

Chapters 2 and 3 describe my research. The overall purpose of this research is to investigate hydrological effects of various widths of commercially strip-thinned silvopastures (ie. 10, 15, 20 m strips). The major question is whether or not there is a relationship between the widths of treatments and the water balance throughout all seasons of the year. The interaction of slope, aspect, and geographical orientation of the strips is also of interest.

In Chapter 2 I investigate responses to strip-thinning treatments in the following variables:

1) Snow accumulation.
2) Timing of peak snow pack.
3) Rates of snow disappearance / ablation.

In Chapter 3 I investigate responses to strip-thinning treatment in the following variables:

4) Volumetric soil water content.
5) Soil temperature.
6) Canopy cover
7) Estimated solar radiation

For my final chapter, Chapter 4, I address the management implications of my research.

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2.0 CHAPTER 2 - INFLUENCE OF COMMERCIAL STRIP-THINNING, OF VARIOUS WIDTHS, ON SNOW ACCUMULATION AND TIMING OF SNOW DISAPPEARANCE IN LODGEPOLE PINE SILVOPASTURES ON THE OKANAGAN PLATEAU OF SOUTHERN BRITISH COLUMBIA

2.1 INTRODUCTION

In snow-dominated watersheds, snow accumulation and dynamics of disappearance are critical to ecological water budgets, human water supplies, and flood mitigation strategies (Winkler et al. 2005; Merritt et al. 2006; Harma et al. 2012). Water volumes contributed by snowpack, snowmelt timing, and water storage are influenced by disturbances, such as timber harvesting, that alter canopy cover and net-evapotranspiration (Pike et al. 2008; Brekke et al. 2009; Islam et al. 2019; Winkler et al. 2021). Snow processes are vulnerable to rapidly changing climatic variables, such as temperatures and precipitation, and further interactions occur at the site-specific level with slope, terrain, solar radiation, and altered canopy cover (Winkler et al. 2014; DeBeer and Pomeroy 2017; Dickerson-Lange et al. 2017). Alternative timber harvesting strategies, such as commercial thinning, may be strategically designed to help conserve ecological values and freshwater systems.

Leaders in water management and hydrological research mostly agree there are knowledge-gaps in the understanding of many hydrological processes at the watershed scale (Lapp et al. 2015; Scherer et al. 2018). Topics of greatest concern in the drought and flood-prone Thompson-Okanagan region of British Columbia, Canada include: total water budgets, effects of forest harvesting, climate change, snow monitoring, and volumes and timing of peak stream flows (Lapp et al. 2015). Most approaches to progressive watershed governance share the fundamental objectives of sustainability, conservation, and ultimately gaining control of above and below-ground water flows to satisfy all other objectives (Pike et al. 2010; Brandes and O'Riordan 2014; Lapp et al. 2015; Scherer et al. 2018). We do have the knowledge and ability to manipulate forest structure in attempts to control hydrological processes, while paying particular attention to the terrain and aspect on which that forest structure is altered.

Snow water equivalent (SWE) is commonly used to discuss the size of the snowpack. SWE represents the depth of liquid water that would drain from a completely melted snowpack. Snow ablation, or disappearance, is often the result of multiple unique processes, which include: melt, sublimation, evaporation, and wind drift (Winkler et al. 2005, DeWalle and Rango 2008). Snow melt is defined as liquid water drained from the snowpack, as snow changes from solid phase to liquid (DeWalle and Rango 2008). The temperature of the snowpack is influenced by ground heat flux, longwave/shortwave radiation fluxes, or fluxes due to additional precipitation such as rain. Latent heat is absorbed during energy fluxes and is released as water is drained from the snowpack. Sublimation involves the direct phase change of solid to gas, with sufficient latent heat flux (DeWalle and Rango 2008). Evaporation may occur when the snowpack approximates 0°C, when water is present, and the atmospheric vapour pressure is less than the saturation vapour pressure of the melting snow surface (DeWalle and Rango 2008). Additionally, snow may disappear from a permanent sampling location due to wind transport.

Snow accumulation, ablation-rate, and timing of disappearance are critical processes that we can gain greater understanding and control over in order to improve forest management (Jost et al. 2007). At the landscape-level, peak snow water equivalent (SWE) and ablation-rates have high spatial variability due to dependence on environmental factors, such as latitude, elevation, and climate. At the site-level, the snowpack is further influenced by slope, aspect, terrain, and tree density or canopy cover (Winkler et al. 2005; Jost et al. 2007; DeBeer and Pomeroy 2017; Dickerson-Lange et al. 2017; Winkler et al. 2017).

Larger canopy openings have been consistently correlated with greater snow accumulation and faster rates of snow disappearance (D'Eon 2004; Winkler et al. 2005; Woods et al. 2006; Veatch et al. 2009). This is explained by increased forest cover resulting in increased interception loss and decreased solar radiation exchanged with the surface of the snowpack (Faria et al. 2000; Pomeroy et al. 2001; Pomeroy et al. 2002). Therefore, wider gaps in the canopy allow more throughfall of snow and more net-radiation to be absorbed by the snowpack.

Open clearcuts have been observed to have 37-75 % greater peak SWE, and 2.4 times greater rates of disappearance, compared to mature forests (Winkler et al. 2005). Wider strip-harvest treatments are expected to accumulate more snow; however, edge effects have been observed to a have a limited influence within a distance approximate to the height of surrounding trees (Spittlehouse et al. 2004). This edge effect has been observed to interact with the aspect and orientation of the forest edge. In the northern hemisphere, ablations are shaded to their north or exposed to sunlight to their south. Sunlight can also penetrate further into the sides south-facing forest edges, providing solar radiation deeper into the stand (Spittlehouse et al. 2004).

Snow ablation in mature forests is believed to be nearly 100 % influenced by net solar radiation; whereas, radiation in clearcuts only accounts for about 75 % of the disappearance (Spittlehouse et al. 2004). This suggests that larger openings are exposed to greater losses attributed to evaporation and sublimation (Winkler et al. 2005; Woods et al. 2006). In combination with greater net-radiation reaching the snow surface, wider openings experience faster rates of disappearance.

Objectives of this study were to investigate how different strip-thinning widths influenced total snow accumulation, snow disappearance rates, and time to total snow disappearance, in both harvested and reserve strips. Interactions between various strip-widths and strip-aspect were also investigated in this study. For all of these observations within the strip-thinning treatments, it is important to acknowledge the edge-effects associated with observing snowpacks along a forest edge (within a tree length of surrounding trees).

2.2 MATERIALS & METHODS

Site Description

The Goudie Agroforestry Pilot Project (GAPP) was an operational-scale silvopasture experiment designed to integrate commercial strip-thinning of timber with interim forage and range for cattle. The blocks were located 20 km east of Kelowna, BC (49.941°, -119.243°), with a mean elevation of 1375 m (**Figure 1**). These sites were within the Okanagan Dry Mild Montane Spruce Biogeoclimatic-variant (BGC)(MSdm1) with site series ranging from 03-06 (Lloyd et al. 1990; Curran et al. 2000). Previously logged in 1977, the stands were replanted with 100 % *Pinus contorta* (lodgepole pine). The stands were 45 years old at the time of harvest, between March and July 2018.

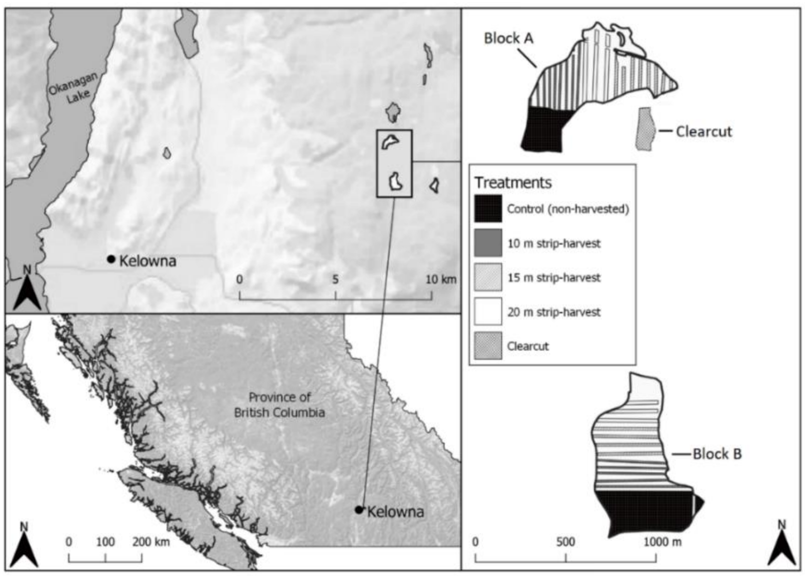

Figure 1. *Map of research sites: Block A (strips orientated north-south), Block B (strips orientated east-west), and a clearcut, which are part the Goudie Agroforestry Pilot Project, were commercially thinned in summer 2018.*

Silvopasture & Commercial Strip-thinning Treatments

The randomized block design included two blocks, which each received four treatments: commercial strip-thinning of widths 10 m, 15m, and 20 m, and a non-harvested control. Between the harvested strips, the width of non-harvested leave-strips are approximately twice the width of adjacent harvested openings. Therefore, each treatment contained two nested parts: harvested strips and leave-strips of proportional widths (i.e., 10 m harvested strip = 20 m reserve strip, 20 m harvested strip = 40 m reserve strip) (**Figure 2**). An adjacent clearcut was also used as a control, which had dimensions of 100 m x 200 m (2 ha). All blocks and controls received treatments during the same year, so stands were the same age.

Additional factors included ground slope and aspect. Block A had strips harvested in north-south orientations; whereas, strips in Block B were in an east-west orientation. Slopes varied between 5 – 12 %.

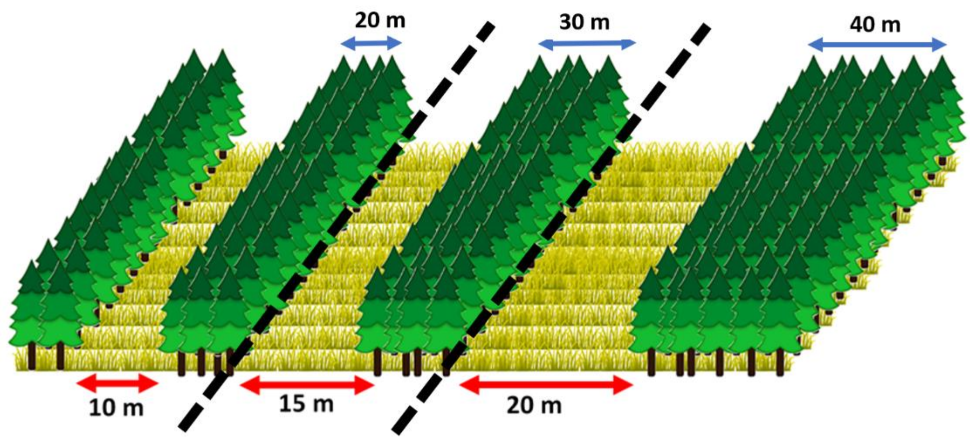

Figure 2*. Simplified diagram of three commercial strip-thinning treatments of varying harvest widths: 10, 15, and 20 m. Leave-strips (reserves) were twice as wide as adjacent harvest openings. Actual treatments did not alternate as depicted in the diagram; several strips of the same width were cut in treatment units as seen in Figure 1.*

A map of snow sampling locations can be found in Appendix D (Figure D.1.).

Climate

A climate station was installed in the clearcut. A tipping-bucket rain gauge (HOBO RG3-M) was mounted 1.5 m above ground, which continuously measured and recorded rainfall with a datalogger (HOBO UA-003-64). An air temperature sensor (HOBO S-TMB-M002) was also mounted 1.5 m above ground with a solar radiation shield (HOBO M-RSA) and continuously recorded every 30 min with a datalogger (HOBO H21-USB).

Three nearest weather stations, owned and operated by the Government of B.C., were used to determine average windspeed and direction on the plateau: Kettle 2 (1341 m), Beaverdell (807 m), and Idabell 3 (1300 m).

Snow

Snow depth and snow water equivalent (SWE) were measured for two consecutive years (2019-2020). Measurements began at peak snow accumulation, immediately before anticipated melt. Spot forecasts (SpotWx 2019) and two regional automated snow measurement stations were monitored for accurate timing of peak snowpack (Mission Creek & Penticton Creek). Snowpacks were measured on two or three-week intervals and the frequency of measurements increased to every 6-8 days as complete disappearance approached.

Sampling followed a systematic stratified design. Each treatment, in each block, received 10 samples. In total, there were 160 sampling locations. Strips in the center of each treatment area were selected for observation, in order to minimize edge effects. Strip selection was also intended to overlap concurrent research on the site (Kega 2021). Sample locations were in 20 m intervals, along 180 m linear transects, which ran directly down the center of each selected strip, parallel to the strip orientation. Intervals of 20 m were selected to ensure samples were independent of each other; point separations of greater than 15 m have not been spatially correlated (Winkler and Moore 2006). Transects had a buffer of 25 m from roads or treatment boundaries. The start of each transect began 25 m from the forest edge adjacent to the nearest road. If strips were shorter than 230 m, transects were split into two strips.

A metric Federal snow sampling tube, with calibrated spring scale, was used to measure snow depth and SWE (Winkler et al. 2015). Each snow sampling location received an ID number, while bamboo stakes with flagging tape were placed as permanent markers. All sequential snow samples occurred within 1 m of the same markers over the two years (Winkler et al. 2015). Measurements with the Federal sampling tube are believed to have maximum potential errors of 7-12% (Winkler et al. 2005). Sample locations were not allowed within 1 m of the base of trees or shrubs of any size.

Peak snow accumulation was filtered by finding the maximum value of SWE at each unique sample location for each year. Between sampling dates, ablation rate was calculated by dividing the observed change in SWE by the number of days between samples. Average daily ablation rates were calculated by peak (maximum) SWE, divided by the number of days between peak SWE and snow disappearance.

At the sampling location, snow disappearance was determined when greater than 50 % of the snow had disappeared within a 1 m radius circle around the bamboo marker (Winkler et al. 2005). If snow disappeared between or after sampling dates, dates of disappearance were estimated based on mean ablation rates between the final two sampling dates.

Canopy Cover & Solar Radiation

Hemispherical canopy photos were taken at each snow sampling location. A full-frame digital camera (Canon 5D Mark III) was used with a 180° hemispherical lens (Meike 6-11mm F/3.5). A flash-mount bubble level was used to level the camera on a tripod, 0.5 m above ground, facing directly up in the zenith direction. The top of the camera was orientated north (0°), sighted with an aiming stick and compass. Photos were captured on overcast and smokey days, because diffused light optimizes the post-processing of images. GPS waypoints of each sampling location were averaged for 2 minutes with a Garmin eTrex 20.

Gap Light Analyzer software (GLA v2.0) was used to estimate canopy cover and solar radiation from the photos (Frazer et al. 1999). The software calculates canopy openness as the proportion of white pixels (sky) to black pixels (non-sky) in the images. Images were pre-processed with a blue light filter to optimize contrast and thresholding. Images were registered with initial cursor points at geographical north (0°). Users must determine a "threshold" for each individual image, which is the sensitivity of each pixel to accurately be classified as either a sky (white) or non-sky (black) pixel. Thresholding was completed manually, with pixel values ranging between 100-140 where all tree branches and foliage were in focus and light-gaps matched original photos. Latitude, longitude, elevation, slope, and aspect of each sampling location were entered into the site configuration settings. Sun tracking was configured for snow season (Nov 1 – Apr 30), with 16 azimuth regions, and 4 zenith regions, with a solar time step of 2 minutes. Solar radiation was modelled with a solar constant of 1367 W/m^2, cloudiness index of 0.5 kt, spectral fraction of 0.5, and beam fraction of 0.5. The universal overcast sky model (UOC) was used for sky-region brightness, with a clear-sky transmission coefficient of 0.65. The parameters mentioned above are recommended as default settings for GLA software by the software creators, as they are an average from peer-reviewed studies with many sampled locations in North America (Frazer et al. 1999).

Tree Height and Density

Airborne light detection and range (LiDAR) was used to estimate tree height and density. A remotely piloted aircraft system (RPAS) included a DJI Matrice-300 RTK, with DJI RTK ground station, and DJI Zenmuse L1 LiDAR payload. Raw point clouds were archived as LASer (.las) files with DJI Terra software.

LASer(.las) files were analyzed with R (version 4.1.2 2021; RStudio 2021.09.1+372, 2021) and the "*lidR*" package (version 4.0.2)(Roussel et al. 2022). Ground points were classified with the cloth simulation filtering (csf) algorithm. Z (height) coordinates were normalized with the triangulated irregular network (tin) algorithm. Individual trees were selected with the "*locate_trees()*" function based on a local maximum filter (lmf) with diameter of 3 m. LASer(.las) files were clipped to circular 5.64 m radius plots either directly centered on, or directly adjacent to, snow sampling locations.

Data Analysis

Data were analyzed in R (version 4.1.2 2021; RStudio 2021.09.1+372, 2021) using a value α=0.05 as the threshold for statistical significance. Data distributions were assessed graphically with plotted residuals and Shapiro-Wilk's test for assumptions of normality and equal variances. Levene's test was used for assessment of homogeneity of variances.

The snow measurement data met parametric assumptions and included both random and fixed variables, so a mixed-effects general linear model was used for analysis. "lme4" and "lmerTest" packages were used in R, which depend on Satterthwaite's method of approximation for p-values (Bates et al. 2015, Kuznetsova et al. 2017). Fixed effects in the models included treatment (strip-width) and block (strip-orientation). Canopy openness (100 - canopy cover %) was used as a continuous independent variable representing the treatment, as harvested strip-width directly influenced the canopy openness. Strip-width was used in some analyses as a categorical variable, but canopy openness was found to better capture the uniqueness of each sample location while accounting for structure of the forest edge (i.e. beetle attack, natural canopy gaps, stem density, and variability in tree heights). Geographical strip-orientations were differentiated by block, which was used as a fixed effect due to the effect of strip-orientation on the dependent variable. Sample date was used as a random effect, because there was year-to-year variability in the intercept, as well as interannual variability in the slope of the association between SWE and the fixed effects. Time and interannual climatic variability were not variables of interest, so random intercepts were used for each sample date. Sample points were spaced at 20 m, so samples were assumed to be independent of each other (Winkler and Moore 2006). Post-hoc Tukey-HSD tests were used for pairwise comparisons.

Estimated solar radiation also met parametric assumptions. A non-linear regression model was also used to compare transmitted direct radiation between blocks, plotted by distance from forest edge as a percentage of adjacent trees. BasicTrendline package was used for the non-linear regression model (Mei et al. 2018).

Canopy cover data met parametric assumptions, so ANOVA with post-hoc Tukey-HSD tests were used. ANOVA was also used to compare some effects within a single year, such as with days to complete snow disappearance. Games-Howell post-hoc tests were used for some comparisons, due to its leniency of non-equal variances.

2.3 RESULTS

Site Characteristics and Climate

Elevations of snow sampling locations ranged from 1349-1395 m and slope ranged from 1-10°. The clearcut was flattest with mean slope of 1.3°, non-harvest areas had a mean of 3.9°, and slope across treatments were statistically similar with means of 5-7° ($P=0.8$). North-south orientated strips (Block A) had a mean elevation 20 m greater than east-west strips (Block B) ($P<0.001$).

Tree heights ranged from 6.8 to 23.4 m ($\bar{x}$ = 18.7 m).Canopy cover was similar within treatments, between blocks ($P>0.60$). One exception was the 15 m strips having 3 % greater canopy cover in strips orientated east-west compared to strips orientated north-south, 50.6 and 47.5 % respectively ($P=0.02$). Mean canopy cover of reserve-strips between blocks was similar (80-81 %).

During the spring melt (April 1 – May 15), air temperatures in the clearcut were similar between both years, with similar number of days and nights above 0 °C **(Table 2.** There were 17 more cumulative degree days, greater than 0 °C, in 2019 compared to 2020. There was more rain in 2020, relative to 2019. In 2020, there was 59.6 mm more total precipitation than in 2019. Also in 2020, 52.2 mm of precipitation fell in the first week of May alone, which occurred with rapid simultaneous snow disappearance across all treatments, primarily due to rapid melt. Wind predominantly blew north to south, or south to north, between Nov. 1 and May 1 **(Figure 3. Average** wind speed and direction for three climate stations owned and operated by the BC Government, of nearest proximity to the Goudie Agroforestry Pilot Project. Wind speed and direction were averaged during the period of snow cover between Nov. 1 – May 1.

Table 2. *Summary of climatic variables observed during a period between peak snow accumulation and total snow disappearance (March 1 – May 15) in 2019/2020 at the Goudie Agroforestry Pilot Project. Snow water equivalent (SWE); snow water density (SWD); cumulative degree days greater than 0°C (CDD >0°C).*

Year	Max. Mean SWE (cm)	Max. Mean Snow Depth (cm)	Max. SWD (%)	# of days above 0 °C	# of nights above 0 °C	CDD (>0°C)	Total precip (mm)	Avg. Max. Temp. (°C)	Avg. Min. Temp . (°C)
2019	13.1	62.1	30.6	45	7	236	27.4	10.3	-2.8
2020	22.6	74.6	36.0	43	7	219	87.0	9.4	-4.1

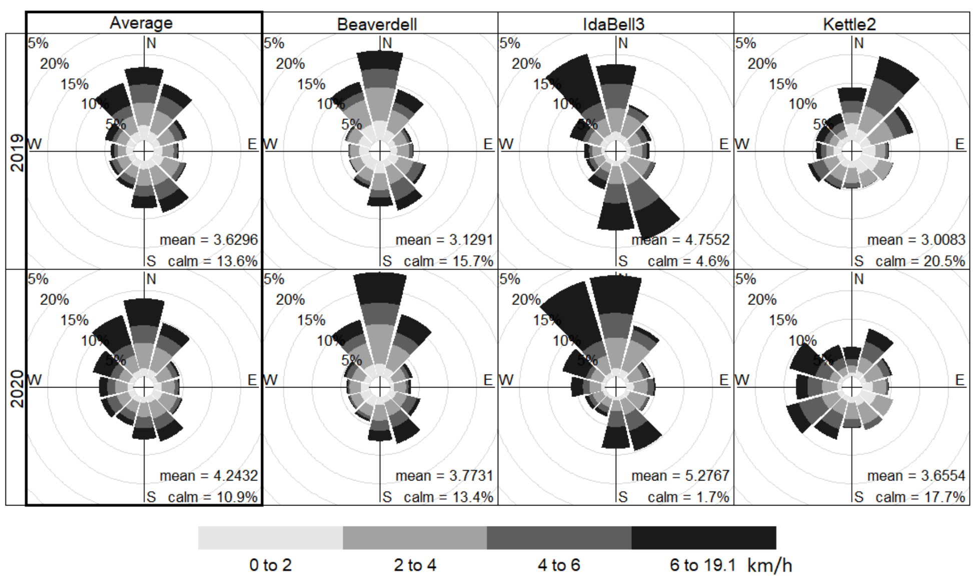

Figure 3*. Average wind speed and direction for three climate stations owned and operated by the BC Government, of nearest proximity to the Goudie Agroforestry Pilot Project. Wind speed and direction were averaged during the period of snow cover between Nov. 1 – May 1.*

Snow Accumulation

The mean snowpack was 75 % greater in 2020 than 2019 (**Table 2**). Greater snow accumulation brought less variability between harvest treatments in 2020. Peak snow accumulation in 2020 had 73 % greater mean snow water equivalent (SWE), 20 % greater depth, and 18 % greater density than in 2019 (averaged across all treatments).

Snow water equivalent (SWE) increased with canopy openness ($P<0.001$, $R^2=0.74$) (**Figure 4**). There was an interaction with strip-orientation, where greater increase in SWE per unit increase in strip-width was found in north-south orientated strips ($P<0.001$). At peak accumulation, the narrowest strips (10 m) increased snow accumulation relative to non-harvested controls by 54 % ($P<0.001$). The widest strips (20 m) accumulated 12 % more SWE than 10 m strips ($P<0.001$). In both years, 20 m strips retained more snow than the clearcut. The 20 m strips had a peak accumulation of SWE which was 11.4 % greater than the clearcut, with both years combined ($P=0.001$) (**Figure 5**).

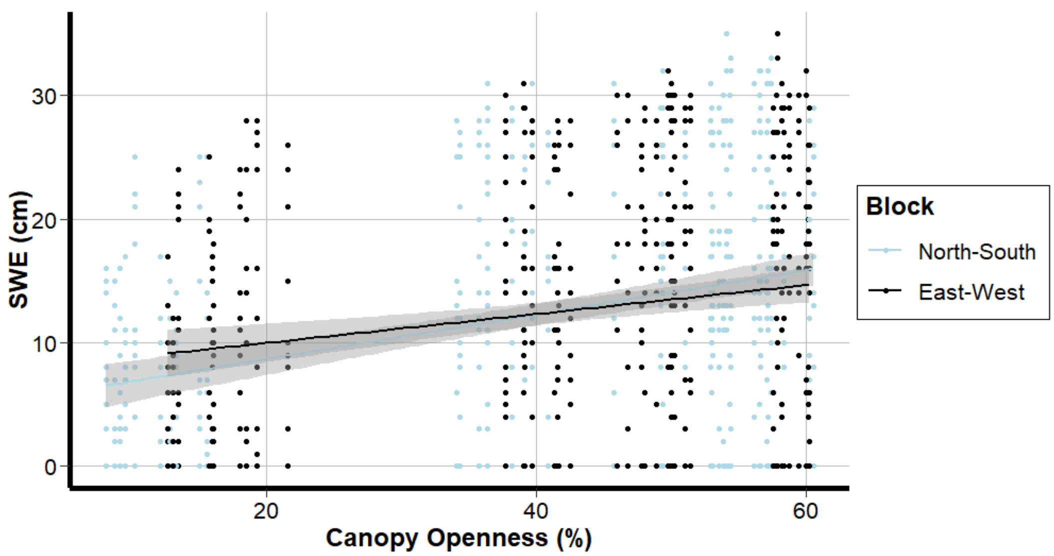

Figure 4. *Snow water equivalent (SWE) in commercially strip-thinned treatments of various widths (10, 15, and 20 m) expressed as canopy openness (%) at time of peak snow accumulation. Non-harvested areas were included as controls. SWE was measured during the years 2019 and 2020. Mixed effects linear model was used with fixed effects: canopy openness & strip-orientation, sample date was a random effect. Snow water equivalent (SWE) increased with canopy openness ($P<0.001$, $R^2=0.57$, $n=160$).*

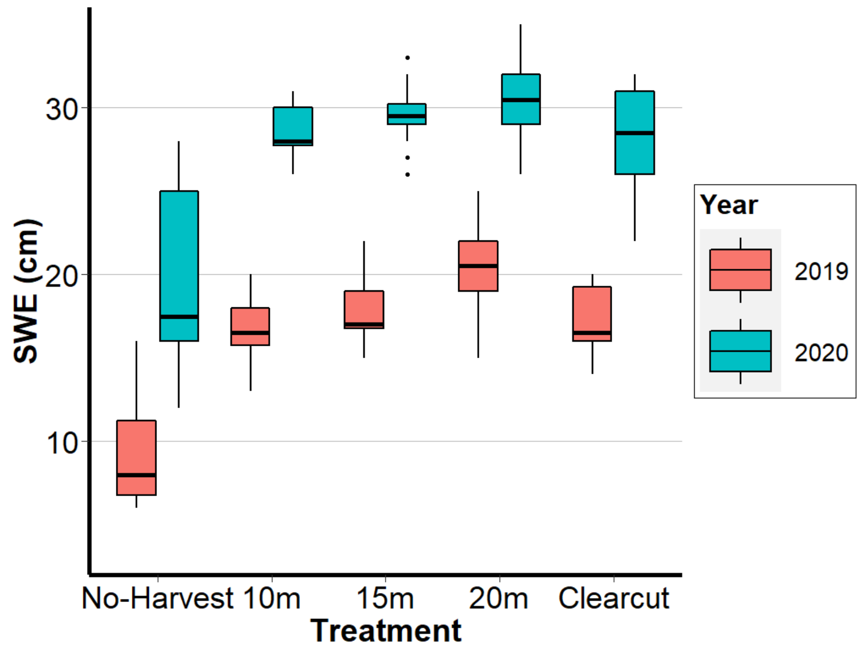

Figure 5. *Peak snow accumulation, measured as snow water equivalent (SWE), in commercially strip-thinned treatments of various widths (10, 15, and 20 m) measured on a single day of peak snow accumulation. The dates of maximum snow accumulation for majority of treatments were April 26, 2019, and April 24, 2020.*

Snow Ablation Rates

Differences in ablation rates between thinning treatments were only observed in 2019. In 2019, east-west strips had a faster mean ablation rate than north-south strips, with a difference of 0.4 mm/day (12 %) (P=0.028, n=30). The greatest differences in ablation rates were observed between March 8-29, 2019, when north-south strips lost –-15 % of the mean snowpack while east-west strips gained +13 %. During this period, 10 m east-west strips gained 4.5 cm SWE, which contributed to 27 % of their total peak accumulation. 15 m east-west strips maintained zero change during this time; whereas, 20 m east-west strips lost 4.6 cm, or 22 % of their peak accumulation. Snow disappearance in 2020 was almost simultaneous with rain and warming events, while ablation rates were consistent across thinning treatments.

Snow Disappearance

Patterns of snow disappearance were inconsistent between both years. In 2019, harvested strip-width had no effect on the number of days for snow to disappear in the center of the strips. However, in 2020 snow in harvested east-west strips completely disappeared in a mean of 5.3 days before the north-south strips (P<0.001). In 2020 there was an interaction between treatment and strip-orientation. Snow in harvested 20 m east-west strips disappeared at least 5 days before any other treatment, and 9 days before strips of equal width orientated north-south (P<0.001) (

Table 3).

Table 3. *The number of days between peak snow accumulation and complete snow disappearance in commercially thinned strips of varying widths (10, 15, 20m) in the Goudie Agroforestry Pilot Project during snowmelt of 2019 and 2020. Snow was measured in the center of the harvested strips. Means were compared with a Games-*

		2019				**2020**	
	NS	**EW**	**P-value**		**NS**	**EW**	**P-value**
10 m	52.6	54.4	0.33	**10 m**	68.8	65.9	0.175
15 m	52	54.5	0.13	**15 m**	69.7	65.8	0.042
20 m	53.3	52.2	0.55	**20 m**	69.3	60.1	<0.001
Mean	52.6	53.7	0.287	**Mean**	69.3	63.9	<0.001

Howell post-hoc test. NS= north-south, EW=east-west.

Further treatment effects on snow disappearance were found in the reserve-strips, where trees remained between the harvested strips. In both years, snow disappeared in reserve strips orientated east-west before any other treatment. In 2019, reserve-strips orientated east-west disappeared 10.2 days before reserve-strips orientated north-south (P<0.001). In 2020, a similar effect was observed with a difference of 4.7 days (P<0.001) (**Table 4**).

Table 4. *The number of days between peak snow accumulation and complete snow disappearance in leave-strips of commercially thinned stands of varying widths (20, 30, 40m) in the Goudie Agroforestry Pilot Project during snowmelt of 2019 and 2020. Snow was measured in the center of the leave-strips. Means were compared with a Games-Howell post-hoc test. NS= north-south, EW=east-west*

	2019				**2020**		
	NS	**EW**	**P-value**		**NS**	**EW**	**P-value**
20 m	41.1	29.1	0.024	**20 m**	60	57.6	0.088
30 m	43.5	38.4	0.034	**30 m**	65	60.3	0.034
40 m	47.1	33.6	<0.001	**40 m**	64.5	57.8	0.002
Mean	43.9	33.7	<0.001	**Mean**	63.2	58.6	<0.001

Solar Radiation

The effect of harvested strip-width on estimated transmitted direct radiation was dependent on the height of surrounding trees and distance from the forest edge. Overall, direct radiation increased with the distance from forest edge in proportion to the surrounding tree heights (P<0.001) (**Figure 6**). There was an interaction, as north-south orientated strips had greater increases of estimated direct radiation with increasing strip-width, compared to east-west orientated strips (P<0.001).

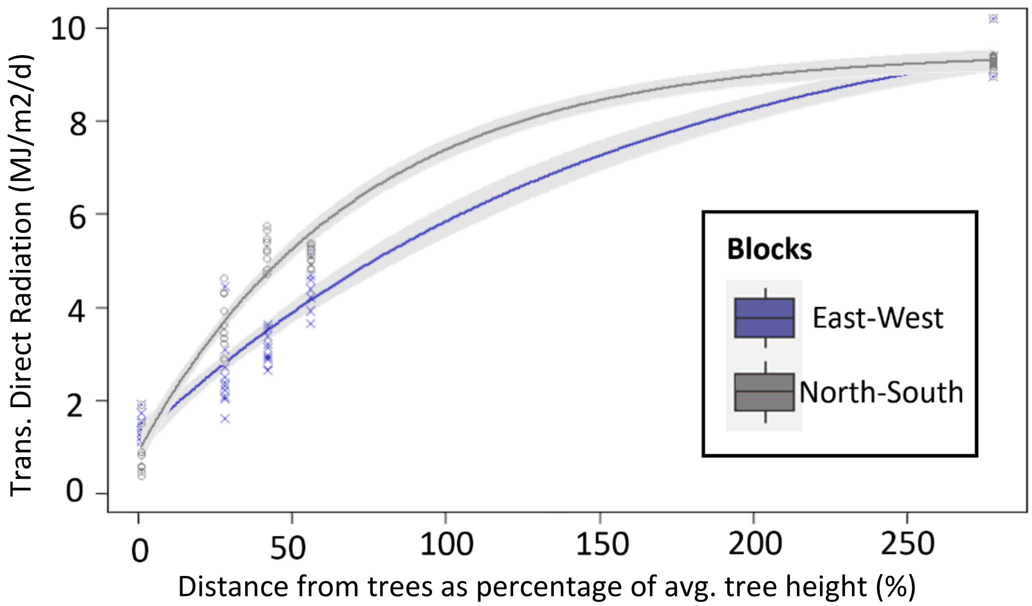

Figure 6. *Nonlinear regression models of estimated transmitted direct radiation at snow measurement locations in the center of harvested strips of commercially thinned stands of various widths (10, 15, 20m), plotted by distance from forest edge as a percentage of the average height of surrounding trees ($\bar{x}$ = 18.7 m), and by strip orientation (east-west vs north-south). North-south $Y = -8.6\ e^{-0.014\ X} + 9.5$, R^2=0.97, P<0.001. East-west $Y = -9.7\ e^{-0.0065\ X} + 11$, R^2=0.97, P<0.001.*

Differences in transmitted direct radiation in harvested strips, were only observed where distance from forest-edge was equal to, or less than, the height of surrounding trees. The 10 m strips orientated north-south were estimated to receive 1.1 MJ/m^2/day more direct radiation than 10 m strips orientated east-west (P<0.001) (**Figure 7**).

The difference between 15 m strips of opposing orientation, was 2.2 MJ/m^2/day (P<0.001). There was no difference in direct radiation between 20 m strips of opposing orientations (P=0.47). Overall, all harvested strips orientated north-south received 1.3 MJ/m^2/day (36 %) more direct radiation than east-west strips (P<0.001).

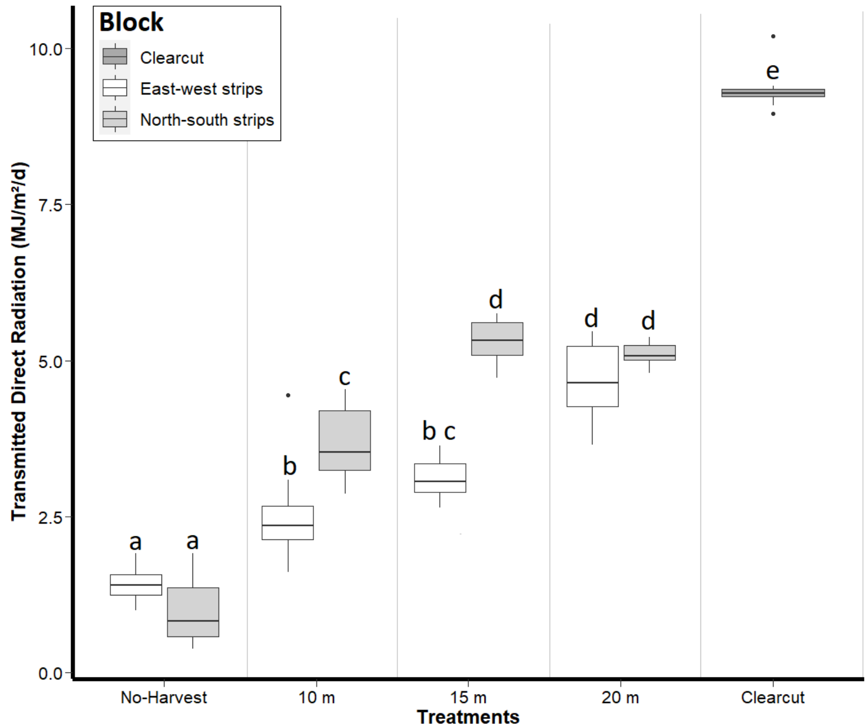

Figure 7. *Estimated transmitted direct radiation in harvested strips of commercially thinned stands of various widths (10, 15, 20m), plotted by treatment and blocks of opposing strip-orientations (north-south vs east-west). Different letters represent P<0.05 on Games-Howell pairwise comparison tests (n=20).*

Transmitted diffuse radiation in the center of 40 m leave-strips (between 20 m harvested strips) was estimated to be 43 % greater than non-harvested areas (P<0.001) and 33 % greater than 20 m leave-strips (P<0.001). Whereas, a difference in directly transmitted radiation between 20 and 40 m leave-strips was not observed (P=0.99). The 20 m leave-strips had mean canopy cover of 83.1 %, while 40 m leave-strips had canopy cover of 77.6%, a difference of 5.5% (P<0.001).

Snow results are summarized in Appendix E (Tables F.1 – F.10)

2.4 DISCUSSION

The various widths of harvested strips in the commercial stand-thinning treatments influenced snow accumulation, ablation rates, and time to total snow disappearance. These effects were further influenced by the geographical orientation of the strips (north-south vs east-west). The designs of the alternative harvesting strategies affected snow dynamics in the harvested strips, as well as the snow dynamics of the reserve-strips between the harvested strips. The fundamentals of these snow processes have been explained in detail in many previous studies and this experiment put the theories to test, with multiple harvest treatments and orientations, side-by-side within a 100 ha area. Strip-width increments of 5 m (i.e., 10, 15, 20 m strips), in combination with non-harvested areas and a clearcut, provided a fine-scale experiment with a spectrum of canopy-gaps ranging from less-than to greater-than the average height of surrounding trees. This is the first study in B.C. that has examined the snow dynamics in commercially thinned, mid-rotation stands with strips 10-20 m wide. The broad implications of this study are that the chosen strip-widths of commercial thinning operations do influence the volume of snow water equivalent (SWE) at any given time, and also influence the ablation rates, and timing of total snow disappearance. This study provides evidence to suggest that harvesting strategies can be more deeply assessed prior to implementation, in order to determine the effects of the geographical orientation, slope, and aspect of resulting canopy-gaps to control the snowpack in accordance with a broad range of land management objectives.

Snow Accumulation

It is important to highlight the spatial and temporal variability inherent in all repeated-measures snow studies, especially as the climatic variables change year-to-year (Winkler et al. 2005). Most notably was the 73 % difference in peak SWE observed between 2019 and 2020. This study benefitted from capturing such annual variability within a two-year sampling window. It is important to acknowledge that variability, or difference between treatment effects, decreases as snow accumulation increases (Winkler and Moore 2006).

Peak snow accumulation increased with harvested strip-width, which is consistent with previous studies. It has been well established, that canopy-openness has been positively correlated with snow accumulation due to reduced snowfall canopy-interception loss (D'Eon 2004; Winkler et al. 2005; Woods et al. 2006; Veatch et al. 2009). However, it was surprising to see 8-17 % greater accumulation in the center of 20 m strips than in the clearcut of much larger open area. Snow was sampled in the center of the strips, so the center of the widest 20 m strips is only 10 m from forest edge. This 10 m distance is equivalent to 53 % of the adjacent tree heights ($\bar{x}$ = 18.7 m), which is well within the range of influence of forest-edge (Spittlehouse et al. 2004). Although the clearcut was a much larger opening size, this is likely explained by the forest edge providing more shelter in the strips. Although wind was not measured in this study, 20 m strips are likely sheltered by forest edge from wind, and processes of sublimation and evaporation, effects of which may be greater in the clearcut (Spittlehouse et al. 2004; Winkler et al. 2005). All snow samples were taken on linear transects down the center of open- or reserve-strips. All snow sampling locations in harvested treatments had a distance from forest edge that was equivalent to 31 – 123 % of the height of surrounding trees. All snow sampling locations were under influence of edge effect, within one tree length from surrounding trees (Spittlehouse et al. 2004).

This edge effect has been observed to interact with the orientation of the forest edge. Previous studies suggest that greatest snow accumulation occurs in gap-widths 3-8x the average tree-height and which are orientated parallel to the wind (Hoover 1969; Gary 1974). However, in this study, there was no observable influence of strip-orientation on snow accumulation (P=0.61). This is inconsistent with the understanding of interception, sublimation, and redistribution processes occurring at micro-scales (Pomeroy et al. 1998). North-south strips were parallel to the predominant wind direction. North-south orientated strips also had greater increases of estimated direct radiation with increasing strip-width, compared to east-west orientated strips (P<0.001).

Increased solar energy inputs increase probability of sublimation, evaporation. With differences in wind direction and solar radiation between strip orientations it was expected to observe some influence on snow accumulation.

The 40 m leave-strips (between 20 m harvested strips) accumulated 20 % more SWE than 20 m leave strips (between 10 m harvested strips). Wind and sublimination have a greater effect on more exposed, or less sheltered, snowpacks, which may be the case with leave-strips surrounded by wider openings (Pomeroy et al. 2009; Molotch et al. 2004; Molotch et al. 2007; Reba et al. 2012; Rasouli et al. 2014). Narrower reserve-strips had greater canopy-openness, but lesser SWE accumulation. Solar radiation is also a critical factor in snowpack dynamics, as both shortwave and longwave radiation influence the snow energy balance (Stoy et al. 2018; Dombrovsky et al. 2019). Forest structures influence radiation by favouring conditions for either long or shortwave radiation (Essery et al. 2008). Gaps in the forest canopy allow direct transmittance of solar radiation and increased shortwave radiation (Essery et al. 2008). Canopy cover increases longwave radiation to the ground or understory, while decreasing the influence of shortwave radiation (Essery et al. 2008). Tree canopies and stems can retain and emit more thermal energy than the surrounding air (Pomeroy et al. 2009). Longwave radiation emittance from tree canopies and stems will have a greater influence on snow dynamics during periods of lower air temperatures (Pomeroy et al. 2009). Variations of forest structure with different thinning widths, combined with terrain and strip orientation, results in varying levels of long and shortwave radiation.

Since the center of harvested strips and leave-strips were observed, sampling locations were of varying distances from the forest edge. For example, the center of a 20 m leave-strip is only 10 m from the open gap in the canopy, which sunlight penetrates through. Whereas, the center of a 40 m leave-strip is 20 m from the canopy gap, which is beyond a tree length from the forest edge. It is most likely that snow disappeared earlier in narrower leave-strips, due to increased shortwave radiation with more frequent canopy gaps. The canopy cover associated with the 20 m leave-strips also provides shelter for increased longwave radiation below the canopy (Pomeroy et al. 2009).

Snow Ablation Rates

The greatest differences in ablation rates were observed between March 8-29, 2019, when north-south strips lost 15 % of the mean snowpack while east-west strips gained 13 %. During this period, 10 m east-west strips gained 4.5 cm SWE, which contributed to 27 % of their peak accumulation; meanwhile, ablation occurred in all other treatments. These findings were consistent with the estimated transmitted direct radiation, as harvested north-south strips had a mean daily direct radiation of 1.3 $MJ/m^2/day$ (36 %) greater than east-west strips ($P<0.001$). When the path of the sun is overlaid on the forest structure, it helps to visualize the effect of strip orientation on direct solar radiation (**Figure 8**). The suns angle gets steeper towards the earth's surface during summer, which increases solar insolation and transmitted radiation (**Figure 9**). This evidence suggests that the resulting forest structure from the thinning treatments influences the effect of long and shortwave solar radiation and, when combined with wind speed and air temperature, likely contributes to heat exchange between the snow surface and atmosphere (Spittlehouse et al. 2004).

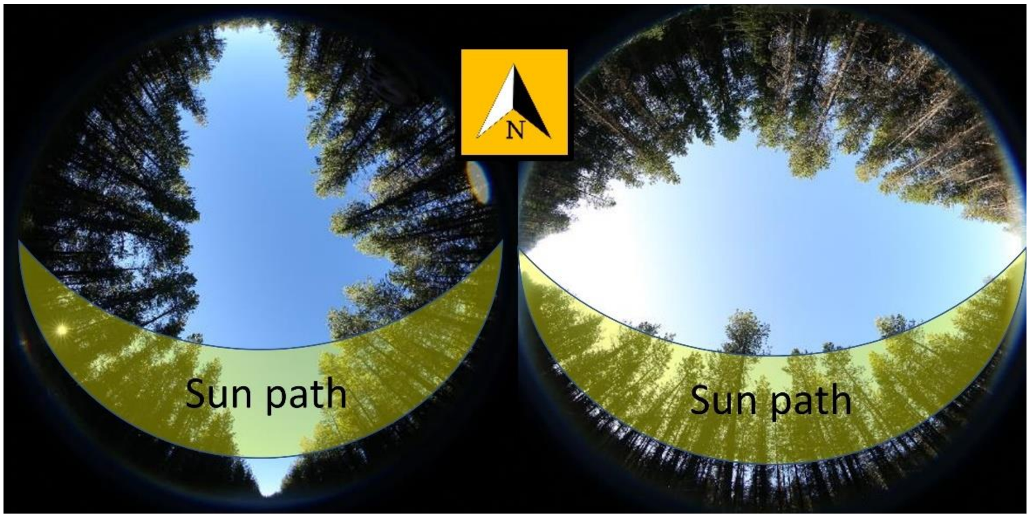

Figure 8. *Visualization of the estimated path of the sun, between Nov. 1 – May 1, in 10 m wide strips, of opposing geographical orientations (north-south vs east-west) harvested in commercial strip-thinning operations in the Goudie Agroforestry Pilot Project. Path of the sun was visualized with Gap Light Analyzer (GLA) software with hemi-spherical photos.*

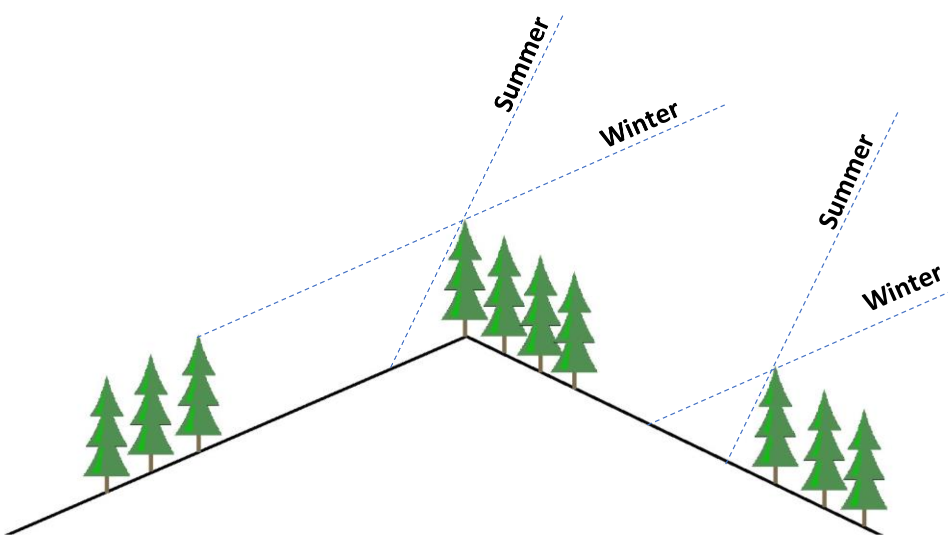

Figure 9. *Diagram of approximate seasonal changes in the angle of the sun and its interaction with terrain, slope, and aspect in the northern hemisphere.*

Snow disappeared sooner in leave-strips and non-harvested areas, relative to harvested areas, due to there being less SWE with increasing canopy closure. Highest ablation rates tend to occur in areas with shallowest snowpacks. Snow tends to disappear quickest near the base of trees. Previous studies have attributed the quicker ablation rates to increased longwave radiation emitted from tree stems (Faria et al. 2000; Musselman et al. 2008; Pomeroy et al. 2009). Sunlight can penetrate further into south-facing forest edges, providing solar radiation deeper into the stand (Spittlehouse et al. 2004). At these latitudes, forest edges are shaded to their north or exposed to sunlight to their south. Sunlight can also penetrate further into south-facing forest edges, providing solar radiation deeper into the stand (Spittlehouse et al. 2004).

Management Implications

With the ultimate goal of sustainable resource management in mind, these results highlight the importance of strategic structural design of forest stands to help achieve objectives. These results suggest that fine-scale differences, such as differences of 5 m in strip-widths and the orientation of these strips, directly influence resources on which timber and forage productivity depend on.

Manipulation of snow accumulation is important both at the watershed-scale and site level, as it determines the amount of water available for reservoir storage, spring runoff, and biological availability for timber and forage productivity (Winkler et al. 2005; Brekke et al. 2009; Hu et al. 2010). These results also remind us that the timing of total snow disappearance depends on the amount of snow allowed to accumulate in that particular area.

Harvested strips that are slightly wider than the height of surrounding trees will accumulate more snow water equivalent than thinner strips or clearcuts with larger openings. If lesser snow depth and faster snow disappearance are required for critical ungulate winter ranges, then narrower strips orientated east-west could be considered for less snow accumulation and faster disappearance rates within reserve strips (Safford 2004).

Since the effects of the forest-edge are the primary causes of these observed snow dynamics, it is recommended to use *site index* or inventory data to make estimates of tree heights. With estimates of average tree heights it is possible to determine appropriate strip-widths to achieve management objectives. It is important to consider the height of the trees for the duration of their expected life, which is why site index is an appropriate variable to consider.

The timing of snow disappearance defines the length of growing season; thus, the timing also defines the limits on biodiversity as the length of growing season combined with moisture availability determine the organisms that the ecosystem can support. Snow insulates vegetation, microbes, biological activity, and chemical reactions in the soil from extremely low temperatures (Pulliainen et al. 2017; Krinner et al. 2018). Snowpack is critical to the carbon balance, both as frost protection and in the timing of disappearance and soil moisture availability that initiates growth of vegetation. The timing of snow disappearance and soil temperature that initiates growth of vegetation, is therefore analogous to carbon sequestration (Pulliainen et al. 2017). Reduced annual snowpack, anticipated with climate change, will have widespread effects on all processes dependent on snow accumulation (Islam et al. 2019).

2.5 CONCLUSION

Commercial strip-thinning and agronomic seeding for operational-scale silvopasture is an alternative harvesting strategy that can influence snow dynamics in both the harvested and reserve strips. These effects were further influenced by the geographical orientation, or aspect, of the strips (north-south vs east-west).

Responses in the snowpack to strip-width were largely due to the proportion of the canopy-gap to the height of surrounding trees. Wider strips accumulated more snow water equivalent (SWE). The 20 m strips even accumulated more snow than the clearcut, likely due to the reserve strips providing shelter from wind and sublimation; whereas, the clearcut is more exposed. Harvested strips that are slightly wider than the height of surrounding trees will accumulate more snow water equivalent than thinner strips or clearcuts with larger openings.

Snow processes have highly variable temporal and spatial patterns, but under certain conditions east-west orientated strips can increase snow accumulation and delay snow disappearance by several days due to shade provided by the southern forest-edge. Orientation of the strips also influenced ablation in the leave-strips, as east-west leave-strips disappeared 5-10 days before any other treatments.

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3.0 CHAPTER 3 – INFLUENCE OF COMMERCIAL STRIP-THINNING, OF VARIOUS WIDTHS, ON SOIL MOISTURE AND TEMPERATURE IN LODGEPOLE PINE SILVOPASTURES ON THE OKANAGAN PLATEAU OF SOUTHERN BRITISH COLUMBIA

3.1 INTRODUCTION

Soil moisture and soil temperature are two of the most critical ecological factors influencing the outcomes of forest and range management. Aspects of soil moisture, including biological availability and storage capacity, link fundamental hydrological processes, from precipitation to groundwater and runoff, to the ecological functions that determine vegetative productivity, diversity, and carbon sequestration (Kupfer and Cairns 1996; Rodriguez-Iturbe et al. 1999; Koster et al. 2004; Hirschi et al. 2010). Whereas soil temperature directly influences the timing and length of growing seasons, overall biomass production, and processes relating to carbon sequestration, such as soil respiration (Peng and Dang 2003; Almagro et al. 2009; Bürli et al. 2021). Alternative forest harvesting systems may be strategically designed to optimize soil moisture availability and water utilization, not only to improve forage and timber productivity, but also to improve flood, wildfire and climate change mitigation

In forests and rangeland, water balance is crucial in determining vegetative productivity and biodiversity. Beyond the broad spatial and temporal patterns of climate and precipitation, soil moisture content at the site-level is dependent on many factors from parent materials of the soil, physical properties and composition of soils, to terrain and topography (Koster 2004). Soil texture, structure, porosity, bulk density, and carbon content all control the distribution of water throughout the vadose zone (Vereecken et al. 1989; Lin et al. 2006). Spatial patterns of soil moisture are further influenced by vegetative cover, leaf-area-index, solar radiation, air temperature, and the volume of water transferred to the atmosphere via evapotranspiration (Teuling and Troch 2005).

The research site used for this thesis was mapped in the Montane Spruce biogeoclimatic zone (Lloyd at al. 1990). These zones typically have wetter soils; therefore, soil moisture may not be a limiting resource to the productivity of lodgepole pine within these zones. In previous studies, east of the Rocky Mountains in similar climate to the montane spruce zones of BC, various soil moisture and nutrient regimes were observed to have little to no influence on productivity of established lodgepole pine stands (Wang et al. 2004). With abundant moisture availability, differences in site productivity may rather be due to differences in temperature and length of growing season associated with elevation (Wang et al. 2004). However, in more temperate and drier climates, soil water content is often a limiting resource for forest productivity and carbon storage (Chimner et al. 2010; Pretzcsh et al. 2012). Soil moisture can also be limiting to land management objectives, as there is often competition between understory vegetation and tree seedlings, as is the case with conifers and tall grasses in drier climates (Wallace et al. 2021).

It is generally understood that timber harvesting immediately increases water availability in the soils and ground due to increased precipitation throughfall and decreased transpiration resulting from the removal of trees (Gebhardt et al. 2014; Korres et al. 2015). Timber harvesting has also been observed to influence transmittance of solar radiation to the ground and understory, as well as increased wind, which together often cause an increase in evaporative losses of ground moisture (Simonin et al. 2007; Traff et al. 2015). Controlling the amount of water yield and runoff caused by timber harvesting is a primary concern for land managers (Zhao et al. 2021). Removal of any amount of trees is expected to increase water yield; however, stand thinning has been observed to lessen the severity of runoff relative to clearcutting (Zhao et al. 2021). Flood mitigation, reservoir volumes, and water quality are top priorities in a community watershed; however, forest planners are also striving for optimal water usage and efficiency (Guerrieri et al. 2019; Arroyo-Rodríguez et al. 2020). In regards to achieving goals of sustainable resource extraction, optimal carbon sequestration, timber and forage productivity and biodiversity, on-site water usage should be optimized to the best of our ability (Arroyo-Rodríguez et al. 2020). Water efficiency is particularly important in drier or drought-prone ecosystems. Forests stands should be designed to be resilient to a range of weather anticipated with climate change, while balancing the water budget to account for objectives at the site-level and also downstream.

Previous studies suggest that soil temperature may be more growth-limiting for *Pinus contorta* (lodgepole pine) than soil moisture in montane forests of higher elevation (Wang et al. 2004). Soil temperature is primarily influenced by transmittance of solar radiation to the ground (Onwuka et al. 2016). Timber harvesting and removal of debris is generally expected to increase soil temperatures due to increased transmittance of radiation (Zabowski et al. 2000).

Previous studies have determined that a minimum soil temperature of 5-6 °C is required for most herbaceous crop and grass seeds to germinate (Dubetz et al. 1962; Singh and Dhaliwal 1972). Germination success of perennial forage species tends to increase with increasing soil temperature; however, optimal soil temperature for germination and growth have been observed to be between 18-26 °C (Dubetz et al. 1962; Singh and Dhaliwal 1972; Morrow and Power 1979). Wheatgrasses have been observed to require 82-98 growing degree days (GDD) to produce their first leaf during the initial growth phase, and between 135-372 additional GDD for the first leaf to develop in the second regrowth phase (Frank 1991). Optimal soil temperatures for root and shoot growth of lodgepole pine seedlings has been observed to be around 20°C (Lopushinsky and Max 1990). Therefore, it is expected that stand thinning may increase the length of growing seasons for timber and forage in these montane ecosystems, by indirectly increasing soil temperatures and cumulative growing degree days.

Combinations of soil temperature and moisture are also pertinent to the conservation and diversity of microbes, forest fungi, and processes of soil respiration (Wilhelm et al. 2017). Larger forest openings have lower carbon to nitrogen (C:N) ratios, greater moisture availability, and warmer soil temperatures which aid in the production of organic nitrogen (Parsons et al. 1994). Increased growing degree days (GDD) have been positively correlated with faster wood decomposition (Finér et al. 2016). There was also found to be a positive interaction with nitrogen content, resulting in faster decomposition of organic materials which have greater nitrogen content and exposed to higher temperatures (Finér et al. 2016). Therefore, balances of soil moisture and temperature not only contribute to carbon sequestration in above-ground productivity, but also below-ground processes of soil respiration and carbon storage.

3.2 MATERIALS & METHODS

Site Description

The Goudie Agroforestry Pilot Project (GAPP) was an operational-scale silvopasture experiment designed to integrate commercial strip-thinning of timber with interim forage and range for cattle. The blocks were located 20 km east of Kelowna, British Columbia (B.C.), Canada (49.941°, -119.243°), with a mean elevation of 1375 m (**Figure 10**). These sites were within the Okanagan Dry Mild Montane Spruce Biogeoclimatic-variant (BGC)(MSdm1) with site series ranging from 03-06 (Lloyd et al. 1990; Curran et al. 2000). Previously logged in 1977, the stands were replanted with 100 % *Pinus contorta* (lodgepole pine). The stands were 45 years old at the time of harvest, between March and July 2018.

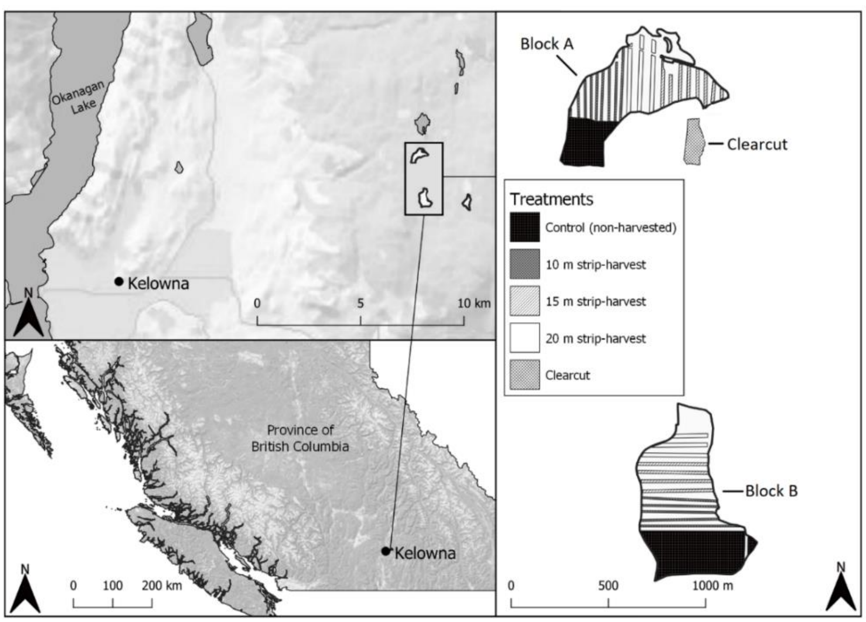

Figure 10. *Map of research sites: Block A, Block B, and a clearcut, which are part the Goudie Agroforestry Pilot Project were commercially thinned in summer 2018.*

Silvopasture & Commercial Strip-thinning Treatments

The randomized block design included two blocks, which each received four treatments: commercial strip-thinning of widths 10 m, 15 m, and 20 m, and a non-harvested control. The blocking factor was strip orientation. Block A had strips in north-south orientations; whereas, strips in Bock B were in an east-west orientation (**Figure 10**). The 5 m difference between strip-widths was anticipated to have a limited effect size on all dependent variables, so 15 m strips were not observed in this particular study, allowing resources and analysis to focus on differences between the narrowest and widest strips (10 - 20 m). All blocks and controls received treatments during the same year, so stands were the same age.

Climate

A climate station was installed in the clearcut. A tipping-bucket rain gauge (HOBO RG3-M) was mounted 1.5 m above ground, which continuously measured and recorded rainfall with a datalogger (HOBO UA-003-64). An air temperature sensor (HOBO S-TMB-M002) was also mounted 1.5 m above ground with a solar radiation shield (HOBO M-RSA) and continuously recorded every 30 min with a datalogger (HOBO H21-USB).

Physical Soil Characteristics

Sixteen soil pits were dug in order to classify the soils and determine soil moisture sampling methods (Lloyd et al. 1990; SCWG 1998). An additional 30 pits were dug with establishment of soil moisture sampling stations, with one pit immediately adjacent to each station. For soil texture and soil organic carbon analysis, samples were collected at two depths (5 cm and 25 cm). Soil texture analysis was completed at the Analytical Laboratory of the BC Government, in Victoria BC, and was reported as percent composition of sand, silt, and clay.

Soil Organic Matter

Soil organic matter (SOM) content was measured using the loss on ignition (LOI) method. Approximately 500 mL of mineral soil was sampled from two depths, 5 cm and 25 cm, from each soil pit. Five sub-samples of 1.5 g were analyzed from each sample. To dry the sub-samples, they were placed into aluminum tin foil pans and heated at 105°C for 24 hours using a YAMATO forced convection constant temperature drying oven (DKN818, Yamato Scientific Co. Ltd). The soils were then weighed on an analytical scale and masses were recorded before placing the dried samples into the muffle furnace. The Barnstead Thermolyne 62700 furnace was used to ignite the soils at 500 °C for 5 hours. Samples remained in the desiccator for at least 30 minutes until room temperature was reached. Samples were weighed and recorded again one final time. The soil organic matter was calculated using the following equation (Wang et al. 2012):

Equation (1):

$$\mathrm{SOM}_{LOI} = \frac{(\mathrm{Mass\ @\ 105°C}) - (\mathrm{Mass\ @\ 500°C})}{Mass\ @\ 105°C}$$

Soil Bulk Density

Soil bulk density was measured and analyzed using the excavation method, due to the high coarse fragment content and rockiness of the soil (Gatea et al. 2018). Mineral soils were sampled as per Canada's National Forest Inventory Ground Sampling Guidelines (NFI 2008).

To maintain randomness in sampling, a two dimensional transect system was used in randomly selected strips of each treatment in each block. This system involved a 90 m transect placed parallel with the strip, and a second perpendicular transect running across the width of the strip. Random numbers were paired for each dimension. Field crews walked up the transect according to the random length drawn, and walked into the strip according to the random width drawn. The lengthwise transect was placed at a 1 m buffer from the forest edge, beginning with a buffer of 25 m from any roads, running parallel to the forest edge. This 90 m transect was binned into quarters: 0-22.5

m, 22.5-45 m, 45-67.5 m, 67.5-90 m. Two random numbers were drawn for each quartered bin to ensure sampling locations were uniformly distributed lengthwise down each strip. Two strips of each treatment were selected, 8 samples were drawn from each strip, resulting in 16 samples per treatment per block including non-harvested control areas. A total of 128 samples were used for the analysis of litter and bulk density.

Live green vegetation was clipped above the sample area. Forest floor was sampled with a 20 x 20 cm template above the hole from which mineral soil was sampled. Mineral and litter were separated individually; fermented and humic layers were included together in the same sample. Average depth of organic layers was recorded. Mineral soil was sampled in a cylindrical hole 10 cm in diameter and 15 cm deep. All material from the hole was included in the sample, including rocks and roots.

Mineral, fermented and humic soil samples were placed in a drying oven at 105°C, and litter samples were dried at 70 °C, for 24 hours or until a constant weight was achieved. Dried mineral samples were weighed before fine fractions were sieved to 2 mm. Fine fraction bulk density was calculated following the volume correction of coarse fragment content (>2 mm), assuming a particle density of 2.65 Mg/m^3 (Blaisdell et al. 2003; Maynard and Curran 2006). Bulk density was calculated using the following equation (Krzic et al. 2010):

Equation (2):

$$Bulk\ Density\ (Mg/m^3) = \frac{\text{Mass of dried fine material}}{\text{Volume of dried fine material}}$$

Coarse fragment content was calculated with the following equation:

Equation (3):

$$Coarse\ Fragment\ Content\ (\%) = \frac{\text{Volume of dried coarse material}}{\text{Total volume of mineral soil sample}}\ x\ 100$$

Soil Moisture & Temperature

Volumetric water content (VWC) was sampled in 10 m and 20 m harvested strips, as well as non-harvested controls, in blocks A and B. From May 2019 to October 2020, volumetric water content was continuously sampled every 30 minutes at two depths (0-10 cm and 25 cm below the soil surface). Soil temperature was also continuously measured at 5 cm depth. Each sampling station consisted of HOBO® Micro Stations (H21-USB) with Decagon® soil moisture sensors (S-SMD-M005) at both depths and HOBO® 12-bit temperature sensors (S-TMB-M006).

Sampling locations followed a stratified systematic approach. Strips in the center of each treatment were purposefully selected to reduce edge effects of other treatments, and also to overlap with snow measurements and other concurrent research on the site (Kega 2021). Stratification criteria included: >25 m from roads and >25 m from different treatments as a buffer for edge effects, centered within the strip between forest edges, mid-slope position, similar slope, similar aspect, no mottling within 35 cm of soil surface, and low enough proportions of coarse fragment material to allow manual digging and placement of sensors. This approach was also systematic, as stations were intended to be placed 50 m apart within the same strip, or on the same slope-position in adjacent strips. However, there was a limitation with the sensors, as they must be placed in a substrate free of rocks and gravel. If rocks were encountered 50 m from the last station, an attempt was made every meter from this point (down strip center) until a rock-free area was found. This approach resulted in full and even coverage of the targeted strata to be sampled. Due to differences in soil texture and SOM between treatments, VWC measurements were not calibrated to ensure standard objective observations.

Data Analysis

Data distributions were assessed graphically with plotted residuals and Shapiro-Wilk's test for assumptions of normality. Levene's test was used to confirm homogeneity of variances. Soil texture data did not have normally distributed residuals, so Kruskall-Wallis ANOVA and Dunn-Bonferroni pairwise comparison tests were used.

Soil organic content was measured in grams (g), this weight was converted to a percentage of the dry-soil weight of the sample. This data was log-transformed to satisfy the parametric assumption of normality. ANOVA and Tukey post-hoc were used for statistical analysis of soil organic content.

Differences in volumetric water content (VWC) between treatments were analyzed with a linear mixed-effects model. Random variables were sampling date and sample station identification number. Fixed variables included harvested strip-width (treatment) and strip-orientation (block). The correlational structure was grouped by random variables: time and station identification number. A Tukey post-hoc was used for pairwise comparison.

Growing degree days equal to or greater than 5 °C were calculated by subtracting 5 °C from the average of daily maximum and minimum temperatures measured at each station. A threshold of 5 °C was selected, because previous studies have determined that a minimum soil temperature of 5 °C is required for most herbaceous crop and grass seeds to germinate (Dubetz et al. 1962; Singh and Dhaliwal 1972). Values were excluded if daily average was less than 5 °C. Cumulative degree days were calculated by summing the accumulation of growing degree days from a specified start date. Differences in growing degree days were analyzed with a linear mixed-effects model. Random variables were sampling date and sample station identification number. Fixed variables included harvested strip-width (treatment) and strip-orientation (block). The correlational structure was grouped by random variables: time and station identification number. A Tukey post-hoc was used for pairwise comparison.

3.3 RESULTS

Climate

Mean monthly temperatures were similar for both years, 2019 and 2020. Maximum temperatures were higher in summer 2020, reaching 32.6 °C; whereas, the maximum recorded temperature in 2019 was 29.4 °C. During the snow-free period (April 1 – September 1) there was more precipitation in 2020 than 2019, with 348 and 217.6 mm respectively. Summer 2020 had higher daytime temperatures and less precipitation (Appendix Figure B.1).

Soil Classification

Soils were determined to be of sandy loam texture, belonging to the order of luvisolic soils, as clay content increased with depth. Presence of mottling, within <50 cm of the surface showed a gleyed soil type which was imperfectly drained. These soils may be classified as gleyed gray-brown brunosolic-luvisols. Photos of two soil pits are displayed in Appendix Figures A.1-A.2. Soil texture composition of sand, silt, and clay-sized particles were consistent between 5 cm and 25 cm depths (P > 0.4) (**Figure 11**, **Table 5**).

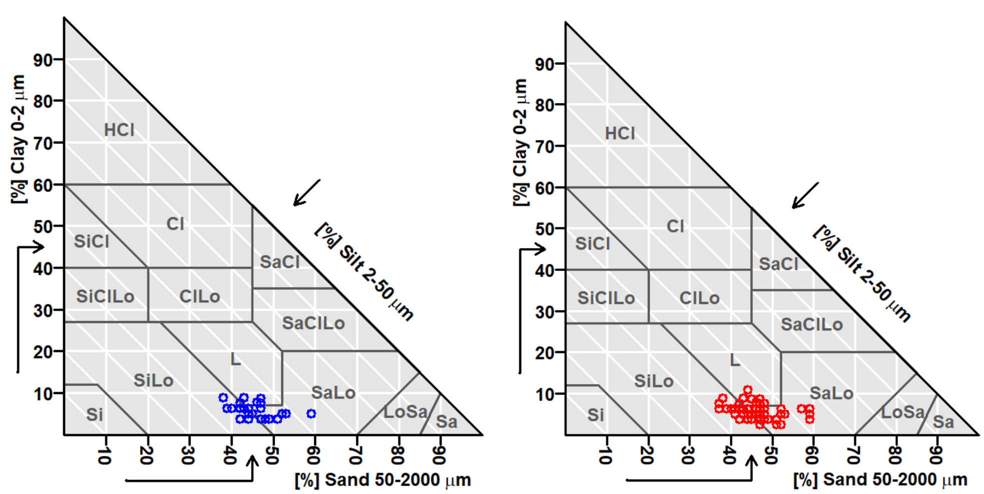

Figure 11. *Sandy loam soil texture determined for locations of all 30 soil moisture sensors on site (all blocks & treatments combined). Left (blue) was sampled at 5 cm depth, right (red) was sampled at 25 cm depth (n=30).*

Table 5. *Means of percent sand, silt, and clay compositions of soil samples taken at depths of 5 and 25 cm, from holes immediately adjacent to soil moisture monitoring stations (N=30).*

Depth	Sand (%)	Silt (%)	Clay (%)
5 cm	45.7	48.5	5.9
25 cm	47.0	47.4	5.6

Composition of sand and silt were consistent across all treatments, at both depths; however, clay composition tended to increase with harvested strip-width. At both depths, clay composition was approximately 2 % greater in 20 m harvested strips compared to non-harvested controls (**Figure 12, Table 8**). The block factor did not have significant influence on this effect (P=0.13) and there were no interactions between blocks and treatments (P=0.64).

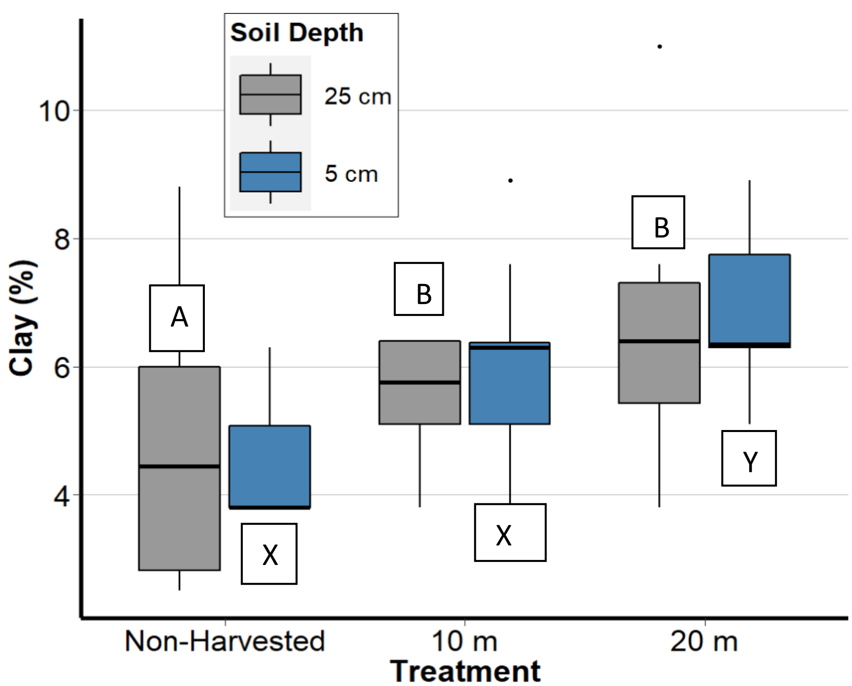

Figure 12. *Clay composition in soils of three treatments (non-harvested controls, 10 m, and 20 m harvested strips), at two depths (5 and 25 cm), sampled one-year post-harvest (2019). Different letters represent P<0.05 on Dunn-Bonferroni pairwise comparison tests, within each series of depth (n=10).*

Table 6. *Results of Dunn-Bonferroni pairwise comparison tests of clay composition in soils of three treatments (non-harvested controls, 10 m, and 20 m harvested strips), at two depths (5 and 25 cm), sampled one-year post-harvest (2019).*

Depth	Treatment Comparison	Z-Stat	P-Value
5 cm	10 m – Non-harvested	2.07	0.058
5 cm	20 m – Non-harvested	3.09	0.006
5 cm	10 m – 20 m	-1.02	0.307
25 cm	10 m – Non-harvested	2.36	0.027
25 cm	20 m – Non-harvested	3.84	< 0.001
25 cm	10 m – 20 m	-1.48	0.138

Soil Organic Matter

On the soil surface, at 5 cm depth, percent composition of soil organic matter (SOM) increased with harvested strip-width (**Figure 13, Table 9**). Mean SOM was 12.7 % in 10 m strips and 20.0 % in 20 m strips (P<0.001). There was an effect of the block factor (P=0.003), as mean SOM in Block B was 4.3 % greater than Block A.

Mean mass of above-ground litter samples also increased with strip-width: 44.5 g in 10 m strips, 48.7 g in 15 m strips, and 61.2 g in 20 m strips. The 20 m strips had a mean litter mass 16.7 g greater (+38 %) than 10 m strips (P=0.027).

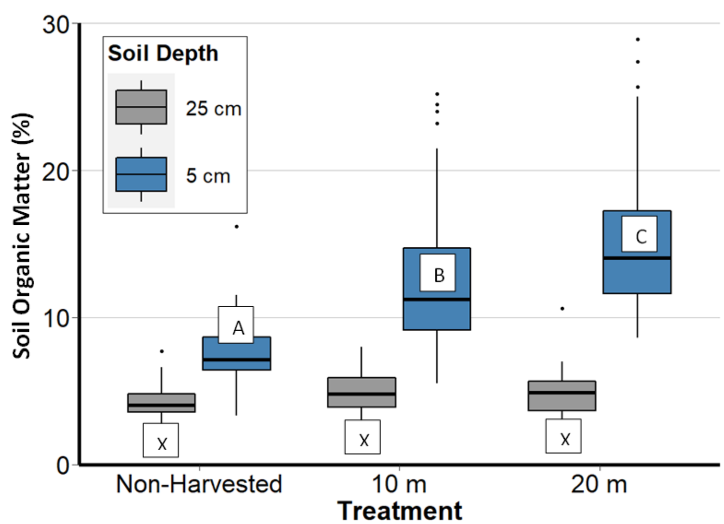

Figure 13. *Soil organic matter (SOM) in soils of three treatments (non-harvested controls, 10 m, and 20 m harvested strips), at two depths (5 and 25 cm), sampled one-year post-harvest (n=25). Different letters represent P<0.01 on Dunn-Bonferroni pairwise comparison tests, within each series of depth (n=5).*

Table 7. *Results of Dunn-Bonferroni pairwise comparison tests of soil organic matter (SOM) in soils of three treatments (non-harvested controls, 10 m, and 20 m harvested strips), at two depths (5 and 25 cm), sampled one-year post-harvest (2019).*

Depth	Treatment Comparison	Z-Stat	P-Value
5 cm	10 m – Non-harvested	5.12	< 0.001
5 cm	20 m – Non-harvested	8.54	< 0.001
5 cm	10 m – 20 m	-3.37	< 0.001
25 cm	10 m – Non-harvested	2.14	0.048
25 cm	20 m – Non-harvested	2.19	0.086
25 cm	10 m – 20 m	-0.047	0.96

Bulk Density

There was a trend for bulk density to increase with harvested strip width. Mean soil bulk densities were 0.87 Mg/m^3 in 10 m strips, 1.04 Mg/m^3 in the 20 m strips, and 0.72 Mg/m^3 in the non-harvested areas. The 20 m strips had 20 % greater mean density than 10 m strips (P=0.057). The 20 m strips had 44 % greater density than non-harvested areas (P<0.001). Results of organic layer observations and coarse fragment content were inconclusive, but included in Table D.1.

Soil Moisture

Maximum soil volumetric water content (VWC), at all depths in all treatments, peaked simultaneously with total snow disappearance in 2020. Peak VWC was not observed in 2019, because instruments were not fully installed until May 30.

VWC on Soil Surface

Differences in VWC were most noticeable on the surface (0-10 cm depth). On the soil surface, during the snow-free season of 2019 (June 1 – October 1), the 20 m strips maintained the most soil moisture with a mean VWC of 0.330 m^3/m^3. Whereas, 10 m strips had a mean of 0.298 m^3/m^3 and non-harvested areas had a mean of 0.259 m^3/m^3. The 20 m strips maintained 11 % greater VWC than 10 m strips ($P<0.001$, $R^2=0.97$), and 20 % greater VWC than non-harvested areas ($P<0.001$, $R^2=0.97$) (**Figure 14**). East-west orientated strips maintained 10 % greater VWC relative to north-south strips, with means of 0.309 and 0.282 m^3/m^3 respectively ($P<0.001$). There was an interaction between strip-width and strip-orientation, where north-south orientation was associated with greater difference in VWC between treatments($P<0.001$).

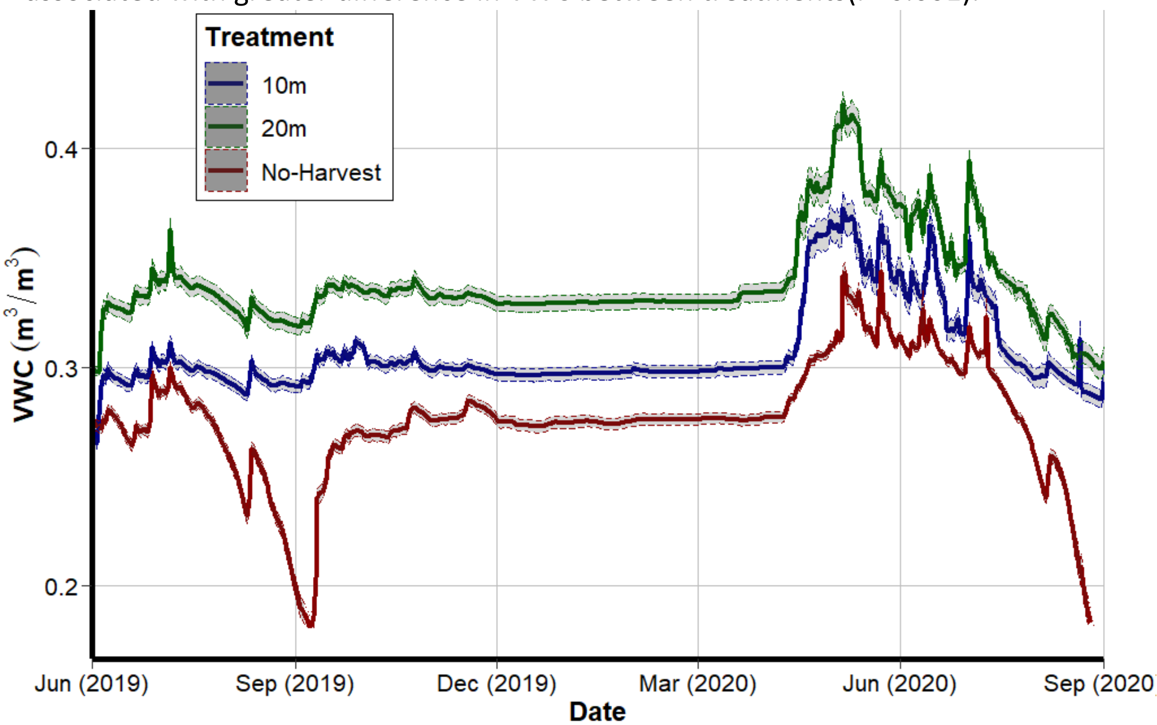

Figure 14. *Surface soil (0-10 cm depth) volumetric water content continuously measured in the center of 10 and 20 m harvested strips and non-harvested control from June 1, 2019, to September 1, 2020. VWC units are a fraction of water volume measured in m^3/m^3. Data includes observations from both north-south and east-west orientated strips of the Goudie Agroforestry Pilot Project (n=10). Shaded ribbons are 95% CI.*

The soil surface, in harvested strips within treatments, maintained equivalent means of VWC during both snow-free and snow-covered seasons. Whereas, non-harvested areas experienced significant reduction of VWC during summer months with minimal precipitation. On the soil surface (0-10 cm depth), during the winter season (November 1, 2019 to April 1, 2020), the 20 m strips maintained 11 % greater VWC than 10 m strips

(P<0.001, R^2=0.98), and 20 % greater VWC than non-harvested areas (P<0.001, R^2=0.98). The 20 m strips maintained a mean VWC of 0.330 m^3/m^3, 10 m strips had a mean of 0.298 m^3/m^3 and non-harvested areas had a mean of 0.276 m^3/m^3

Similar trends were seen in 2020. On the soil surface, during the snow-free season of 2020 (May 1 – October 1), the 20 m strips maintained the most soil moisture with a mean VWC of 0.353 m^3/m^3. Whereas, 10 m strips had a mean of 0.325 m^3/m^3 and non-harvested areas had a mean of 0.290 m^3/m^3. The 20 m strips maintained 9 % greater VWC than 10 m strips (P<0.001, R^2=0.94), and 22 % greater VWC than non-harvested areas (P<0.001, R^2=0.94).

VWC at 25 cm Depth

Strip-width had no effect on soil VWC at 25 cm depth. During the 2019 growing season (June 1 – Oct 1), 10 m and 20 m strips maintained mean VWC of 0.303 and 0.306 respectively at 25 cm depth (P=0.08, R^2=0.96). Both 10 and 20 m strips maintained greater VWC than non-harvested areas, 20 and 22 % greater respectively (P<0.001, R^2=0.96) (**Figure 15**). At 25 cm depth, during the winter season (November 1, 2019 to April 1, 2020), the 20 m strips maintained 1 % greater VWC compared to 10 m strips, with means of 0.320 and 0.316 m^3/m^3 respectively (P=0.001, R^2=0.97). The non-harvested areas had a mean of 0.267 m^3/m^3.

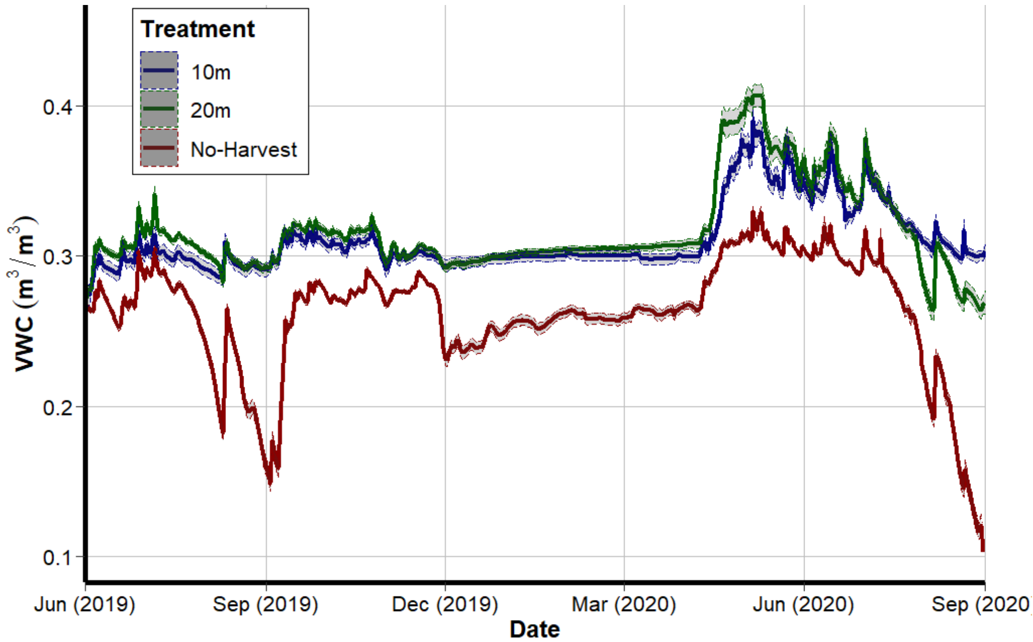

Figure 15. *Soil volumetric water content (25 cm depth) continuously measured in the center of 10 and 20 m harvested strips and non-harvested control from March 1, 2020, to September 1, 2020. Data includes observations from both north-south and east-west orientated strips of the Goudie Agroforestry Pilot Project (n=10). VWC units are a fraction of water volume measured in m^3/m^3. Shaded ribbons are 95% CI.*

Soil Temperature

During the growing seasons of (June 1 – September 1) of 2019 and 2020, harvested strips were associated with higher soil temperatures at 5 cm depth compared to non-harvested areas. The soil surface in 20 m strips had a mean daily maximum temperature 5.2 °C (42 %) greater than non-harvested areas, while mean maximum temperature in 10 m strips was 4.3 °C (35 %) greater than non-harvested areas ($P < 0.001$, R^2=0.76).

There was an interaction observed between strip-width and strip-orientation on the effect of cumulative growing degree days (GDD) above 5 °C during June, July, and August of 2019 and 2020 (P<0.001). In east-west strips, GDD increased with increased strip-width (P = 0.004). East-west orientated 20 m strips accumulated a yearly average of 184 GDD more than 10 m strips (P=.035). Whereas, GDD was not influenced by strip-width in north-south strips (P=0.64).

3.4 DISCUSSION

Biologically available soil water content is often described using the least limiting water range approach (LLWR), which is bound between field capacity (FC) and permanent wilting point (PWP) (Seneviratne et al. 2010). LLWR has frequently been used to assess the limitations or availability of soil water in seedling germination studies (Blouin et al. 2008). During the period of this study, permanent wilting point (PWP) was never observed in any treatment. This was determined by the observation of continuous change in VWC, without ever approaching or achieving a constant PWP. The high non-permanent water table and mottling in this soil confirm that moisture is abundant on this site. Soil moisture may not be a limiting resource for vegetation on this particular site. However, results of this study showed that commercial strip-thinning did have a noticeable effect on soil moisture availability. The width of strips and their orientation both influenced VWC near the soil surface throughout the entire year.

Harvested areas maintained greater VWC than non-harvested areas, which is consistent with previous research (Adams et al. 1991; Gebhardt et al. 2014; Hannah et al. 2015). The differences in VWC are primarily the result of harvesting reducing overall stand transpiration and increasing throughfall (Spittlehouse et al. 2004; Famiglietti et al. 2008; Gebhardt et al. 2014). Although transpiration and precipitation throughfall were not measured in this study, they are major factors to consider with the observations as described in previous literature.

There were observable differences in the responses of soil moisture at the two different depths of 0-10 and 25 cm; greater effect size was observed closer to the soil surface. This was expected, as soil moisture is more responsive to climatic conditions; such as precipitation, temperature, relative humidity, and wind near the surface and response to these environmental factors decreases with depth (McMillan and Srinivasan 2015).

It has been well established that finer soil particle size provides greater surface area for hygroscopic moisture and more micro-pore space for capillary water holding capacity (Susha Lekshmi et al. 2014). This difference in clay composition may have existed in these sites prior to treatments, as litter density and soil organic matter were also greater in wider strips. The approximate 2 % difference in clay content observed between treatments is not expected to have a significant impact on water holding capacity.

Bulk density has been observed to be effected by heavy machinery, but does trend back towards pre-harvest levels after one year post-harvest (Botta et al. 2006; Sakai et al. 2008; Wallace et al. 2021). The observed compaction would not be considered severe and the resulting bulk densities were well within the range (0.7 – 1.15 g/cm^3) previously observed to have no effect on growth of *Pinus contorta* (lodgepole pine) seedlings (Zabowski et al. 2000).

Previous studies have shown how the probability of soil disturbance during harvesting is proportional to stand density (Sowa and Kulak 2008). A denser stand being harvested, results in more felling, pushing, pulling, dragging, scraping, lifting, and transportation of logs, compared to stands with fewer trees. All of these motions of heavy machinery and movement of pieces contribute to soil disturbance. Bulk density is the most common soil property used to assess compaction (Nawaz et al. 2013). It is well understood that increased compaction leads to increased bulk density, which is consistent with the findings of this study. It is important to acknowledge the effects of compaction on bulk density and the differences in clay content observed; however, these are minor factors in the overall effects of these treatments on soil moisture availability.

Soil organic matter content (SOM) was 7.3 % greater in 20 m strips compared to 10 m strips. It has been clearly established that greater SOM increases the water holding capacity of soil (Ise and Moorcroft 2006; Sierra et al. 2015). This trend in SOM was consistent with increased above-ground litter mass observed in wider strips. The observed positive correlation between litter mass and strip width contradicts the results of previous studies, which found a negative correlation between canopy gap size and ground litter (Zhu et al. 2003). Previous studies have found positive correlations between amounts of litter and stand density (Fish et al. 2006). Although harvest treatments were allocated randomly, analysis of pre-harvest timber cruising data suggests that wider strips may have been harvested in areas with greater basal area of timber. Pre-harvest stand density may have been an uncontrolled variable in this study which affected litter inputs, which may indirectly influence organic matter content and water holding capacity of the soil.

Increasing strip width may also increase wind speed and turbulence, which has been shown to increase ground litter (Bilby and Heffner 2016; Webb et al. 2021). Litter input has been shown to increase soil organic matter (SOM) and soil moisture in pine plantations (Yun Wang et al. 2019). Soil texture, SOM, litter inputs, and bulk density may all influence the soil volumetric water content; however, the majority of influence on soil moisture is likely caused by timber harvesting, reduced transpiration, and increased throughfall (Spittlehouse et al. 2004; Famiglietti et al. 2008; Gebhardt et al. 2014).

Soil temperature was greater in both 10 m and 20 m strips compared to forested areas. This resulted in greater cumulative growing degree days (GDD) above the critical threshold of 5 °C. Beneath snow cover, soil temperatures were greater in narrower strips (i.e. 10 m). This observation was likely due to lesser snow-depth in narrower strips, which reduced the insulating capacity of the snow cover. Previous studies have observed air temperatures to have greater influence over soil temperatures when snowpack is reduced (Sanders-DeMott et al. 2018). Although warmer soil temperatures are beneficial for vegetative growth in the spring, reduced snow packs and the resulting reduction of insulation can be detrimental during freeze-thaw cycles with extremely low temperatures, and have the potential to cause root damage or increased herbivory (Sanders-DeMott et al. 2018).

Implications

Soil water content is often a limiting resource for forest productivity and carbon storage in temperate climates (Chimner et al. 2010; Pretzcsh et al. 2012). In some ecosystems, soil moisture has been observed to be a limiting resource for productivity of lodgepole pine (Pretzsch et al. 2012). This research site was mapped in the Montane Spruce biogeoclimatic zone (Hope at al. 1991). It is important to note that these zones typically have wetter soils; therefore, soil moisture may not be a limiting resource to the productivity of lodgepole pine within these zones.

In similar climate to the montane spruce zones of BC, East of the Rocky Mountains, previous studies have found various soil moisture and nutrient regimes had little to no influence on productivity of established lodgepole pine stands (Wang et al. 2004). With abundant moisture availability, differences in site productivity are rather due to differences in temperature and length of growing season associated with elevation (Wang et al. 2004). Although it was determined that moisture is abundant and currently not a limiting resource on the site discussed throughout this thesis, it is important to consider anomalies of drought years or other responses of potential climate change. For example, increased soil moisture availability may improve the resiliency of all vegetation to drought-stress. Frequent narrow strips, that increase stem spacing and decrease stand density, may be more beneficial for wide-scale tree productivity under drought conditions. Whereas, wider strips providing more soil moisture availability and more growing degree days may be more beneficial for growing forage or establishing conifer seedlings.

Nitrogen availability is often another limiting factor for forest productivity (Hunt et al. 1988). In soils, mineralization is the process involving the decomposition of organic nitrogen and release of ammonium (NH_4^+) (Vitousek and Matson 1985). Ammonium may then be converted to biologically available nitrate (NO_3) through the process of nitrification (Jaffe 2000). In montane pine stands, the amount of naturally occurring ammonium is often limited; therefore, there is slow conversion of ammonium to nitrate and biologically available nitrate is usually depleted relatively quickly (Hunt et al. 1988; Jaffe 2000).

Mineralization rates have been observed to be relatively low in lodgepole pine stands, compared to other forest types (Fahey et al. 1985). Sites with warmer temperatures, greater moisture availability, and more aerobic conditions associated with higher coarse fragment content have demonstrated higher rates of mineralization (Hunt et al. 1988; Parsons et al. 1994; Jaffe 2000). The removal of trees, during the commercial thinning treatment, reduces the density of roots in the soil. This reduction of fine-root density has been associated with higher moisture levels, faster N mineralization and increased nitrification (Parsons et al. 1994). However, these effects are not realized until large enough root-gaps have been created. Larger gaps have been observed to have increased mineralization and nitrification rates, thus larger gaps have more available nitrate and total N to lower the C:N ratio (Parsons et al. 1994). Clearcuts in montane lodgepole pine forests have been found to increase soil nitrate (NO_3^-) concentrations 10-40x that of undisturbed control stands (Knight et al. 1991). Therefore, wider harvested strips have the potential to increase rates of mineralization, due to the increased soil moisture and temperature. This effect may be greater in years with limited precipitation and warmer temperatures. These findings also suggest that wider strips may have a greater benefit from fertilization.

The majority of mineralization occurs during snow-free growing seasons (Fahey et al. 1985). In temperate montane forests, nitrogen mineralization has been found to peak in the spring, immediately after snow disappearance (Parsons et al. 1994). Soil temperatures can be warmer beneath snow, relative to open areas or clear cuts, as the snowpack provides insulation (Hunt et al. 1988). If forest floors and soils are not frozen, then decomposition can have an early start beneath the snow. This justifies further research into the dynamics between snow-depth and soil temperature.

Sites with greater water availability are also more resistant to weather anomalies associated with climate change, such as droughts or extreme precipitation events (McLaughlin et al. 2017). Hydrological processes are direct influencers of ecological succession through natural disturbance regimes. Water volumes are directly linked to floods, slides, and avalanches, while atmospheric, soil, and foliar moistures are all related to wildfires. Water inherently shapes our landscapes through these natural disasters; however, these incidents pose a challenge for Emergency Management BC, BC Wildfire Service, and numerous industries.

3.5 CONCLUSION

Commercial strip-thinning has direct effects on surface soil moisture and temperature. The wider 20 m strips maintained greater soil moisture than 10 m strips throughout the year, even throughout winter. The narrower 10 m strips did retain more soil moisture during the drier summer months of 2020, when there were below average rates of precipitation. Strip-orientation also influenced soil moisture during this dry summer. Under dry conditions, east-west orientated strips maintained greater soil moisture than north-south. Greater soil temperatures were also observed in wider 20 m strips, compared to 10 m strips. Soil temperature was greater in both 10 m and 20 m strips compared to forested areas. This resulted in greater cumulative growing degree days (GDD) above the critical threshold of 5 °C.

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4.0 CHAPTER 4 – MANAGEMENT IMPLICATIONS & FUTURE RESEARCH

Extensive harvesting, insect damage, fungal pathogens, and wildfires have severely reduced timber supply in the interior of B.C. (Kurz et al. 2008; Alfaro et al. 2015; BC Government 2018, 2019). Available first-growth timber supplies are expected to continue to decline before reliance will shift entirely onto replanted stands (BC Government 2019). Demand for alternative forest harvesting methods is at an all-time high in Canada and is increasing globally, especially for replanted stands (Fox 2000; Puettmann et al. 2015; Halofsky et al. 2018). Agroforestry is one form of integrated resource management that has the potential to help satisfy multiple levels of objectives, from site-level to watershed scales (Anderson et al. 2008; Udawatta et al. 2011). This study demonstrated how commercial thinning of timber, combined with silvopastural alley cropping of agronomic grasses, may help satisfy multiple land objectives.

In Chapter 1, we discussed six primary criteria which silvopastures on provincial tenure must aim to achieve in British Columbia (B.C.), Canada (**Table 1**). Sustainable resource management involves the assurance of future supply and productivity of natural resources (Gilani and Innes 2020). Priority objectives of the *Forest and Range Practices Act* include stewardship of timber, forage, soils, water, wildlife, and biodiversity (FRPA 2004). Carefully designed silvopastures have the potential to help with sustainable management of each of these resources and provincial objectives.

Alley cropping was the form of silvopasture used in this study, which provided increased habitat, and therefore productivity, of herbaceous forage species utilized by wildlife and livestock. Commercially thinned strips of all widths provided greater forage productivity than un-thinned stands, and forage productivity increased with strip width (Kega 2021).

Timber productivity may be increased with strategic thinning designs. Previous studies have observed thinning of lodgepole pine stands to increase timber productivity by increasing radial growth and sap flow through reallocation of site resources including: water, sunlight, and soil nutrients (Lagergren et al. 2008; Moreno and Cubera 2008; Moreaux et al. 2011; Skubel et al. 2017; Wang et al. 2019). A review of lodgepole thinning experiments determined that stand thinning may increase radial growth and volumes of individual trees, but excessive thinning may reduce the overall basal area and volume of the entire stand up to 20 years post-thinning (Johnstone and van Thienen 2011). Beneficial effects of thinning have been observed at up to 3 m stem spacing (Wang et al. 2019), which is less than one-third of the spacing in our lightest thinning treatment of 10 m stem spacing. This suggests that 10-20 m wide strip-thinning may be too wide of spacing for optimal timber production, but offers a trade-off of microclimates suited for understory and herbaceous forage species. This trade-off can also be viewed as a diversification of economies, which brings its own financial resiliency that may be studied from an economical perspective. National food security and sustainable agriculture are important social values that must also be considered. The effect of strip-width on timber growth is currently being investigated (Spencer unpublished 2022). The effects of net carbon sequestration could also be investigated further to include above and below ground carbon storage, as well as $C0_2$ flux and soil emissions.

The differences in soil bulk density between treatments suggest that harvest operations do bring a recognizable amount of soil disturbance, which is typical with any form of timber harvesting. Bulk density has been observed to be affected by heavy machinery one year post-harvest, but does trend back towards pre-harvest levels over several years (Botta et al. 2006; Sakai et al. 2008; Wallace et al. 2021). Overall, soil disturbance was relatively low, but future harvesting operations may consider winter harvesting in wetter areas to minimize disturbance as much as possible.

With regards to water stewardship, we did observe increased snowpacks in wider strips. The 20 m strips accumulated more snow than the clearcut. There was also greater soil moisture, to depths of 25 cm, in wider strips throughout the entire year. As discussed in Chapter Three, increased soil moisture and temperature with increasing strip-width may accelerate nitrogen mineralization (Hunt et al. 1988; Parsons et al.

1994). Drought stress not only limits the amount of biologically available moisture for vegetation, but also limits microbial activity, soil respiration, nitrogen mineralization, and nutrient availability (Wilhelm et al. 2017). Adequate soil moisture is necessary for successful fertilization treatments (Cole et al. 1990; Rose and Ketchum 2011). Further research may explore the interaction between strip-width and efficacy of fertilization treatments with the optimal combination of soil moisture and temperature.

It is important to note that the observed effects of strip-thinning widths on hydrological processes are proportional to the ratio of strip-width to surrounding tree heights. Therefore, the desired strip-width will depend on the biogeoclimatic zone, site index, and tree species in question. Furthermore, it is essential to consider the current height of the stand, growth rates, and potential heights during the period for which foresters are planning.

Soil moisture can also be limiting to land management objectives, as there is often competition between understory vegetation and tree seedlings, as is the case with conifers and tall grasses in drier climates (Wallace et al. 2021). Soil moisture did not appear to be a limiting resource on this site; however, moisture regimes continue to change with climate change. Future studies may investigate the effects of strip-thinning on a broader watershed scale, including: peak stream flows, ground water, and optimal water usage on site.

Snow-depth and tree cover are critical factors that influence ungulate winter ranges (UWR) (Safford 2004). Narrower strips would be more beneficial in UWR due to reduced snow accumulation. An east-west orientation of these narrower strips was also observed to cause quicker snow disappearance in reserve strips, between harvested strips. Quicker snow ablation and earlier growth of forage is essential for ungulates, such as moose and mule deer (Safford 2004). Land managers must consider the widths of strips and how the aspect and orientation of those strips influences wildlife habitat.

A mixture of various strip-widths and orientations over diverse terrain, results in a diversity of microenvironments, which in turn results in increased biodiversity (Wei et al.

2020). Diversity of microenvironments leads to diverse timings of snow disappearance, seed germination, and vegetative growth. In this way, an assortment of thinning treatments on a single site can achieve objectives of biodiversity.

Alternatively, these observations can be used to implement control over more uniform and desirable rates of ablation and timing of disappearance. More control over the timing of snow disappearance may be used to influence the timing of forage availability. We observed significant differences in cumulative growing degree days, in soil temperature, between the various treatments. Stands can be strategically designed to increase the amount of growing degree days, which has the potential to facilitate secondary re-growth phases in herbaceous forage (Frank 1991). Manipulation of forest structure to maximize solar radiation, soil temperature, and water availability can ultimately be used to provide increased forage quality and quantity for livestock and wildlife.

In regards to climate change mitigation, thinning of lodgepole pine has been suggested to help offset the negative effects of drought by reallocation of moisture availability (Misson et al. 2003; Simonin et al. 2007; Kohler et al. 2010; Rodríguez-Calcerrada et al. 2011; Sohn et al. 2013; Elkin et al. 2015; del Río et al. 2017; Ambrose et al. 2018; Cabon et al. 2018; Park et al. 2018). Sites with greater water availability are more resistant to weather anomalies associated with climate change, such as droughts or extreme precipitation events (McLaughlin et al. 2017). Hydrological processes are direct influencers of ecological succession, through processes which influence vegetative productivity and through natural disturbance regimes. Water volumes are directly linked to floods, slides, and avalanches, while atmospheric, soil, and foliar moistures are all related to wildfires. Water inherently shapes our landscapes through these natural disasters; however, these incidents pose a challenge for Emergency Management BC, BC Wildfire Service, and numerous industries.

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5.0 APPENDIX A

Figure A.1. *Soil pit displaying the sandy loam texture of brunosolic gray luvisolic soil. Bt horizon has higher clay content than Ae. Btg horizon from water table within <50cm of surface. The water table was at a depth of 42cm.*

Figure A.2. *Soil pit displaying the sandy loam texture of brunosolic gray luvisolic soils. Bt horizon has higher clay content than Ae. Btg horizon from non-permanent water table within <50cm of surface. Water table was at a depth of approximately 40cm.*

6.0 APPENDIX B

Table B. 1. *Summary of mean maximum daily temperatures and monthly precipitation sums by month and year observed at the Goudie Agroforestry Pilot Project during 2019-2020.*

	2019		2020	
	Mean Max. Daily Temp. (°C)	Precip. Sum (mm)	Mean Max. Daily Temp. (°C)	Precip. Sum (mm)
Jan	-	-	-1.9	16.2
Feb	-	-	0.6	22.4
Mar	12.1	-	3.0	18.4
Apr	7.6	20.8	7.7	17.8
May	16.0	27	13.4	160
Jun	17.6	78.4	15.7	104.8
Jul	19.9	56.8	21.2	53.4
Aug	22.3	34.6	22.3	12
Sep	13.9	88.4	18.7	-
Oct	5.6	35	-	-
Nov	2.7	22	-	-
Dec	-1.0	24	-	-

7.0 APPENDIX C

Figure C. 1. *Photo facing east in 20 m leave-strip, between 10 m wide harvested strips. Block B, strips orientated east-west. Date taken: March 29, 2019.*

Figure C. 2. *Photo taken facing south. Photographer was standing in 15 m wide harvested strip, between 30 m leave-strips. Snow is still visible on north half of 30 m leave-strip. Block B, strips orientated east-west. Date taken: March 29, 2019.*

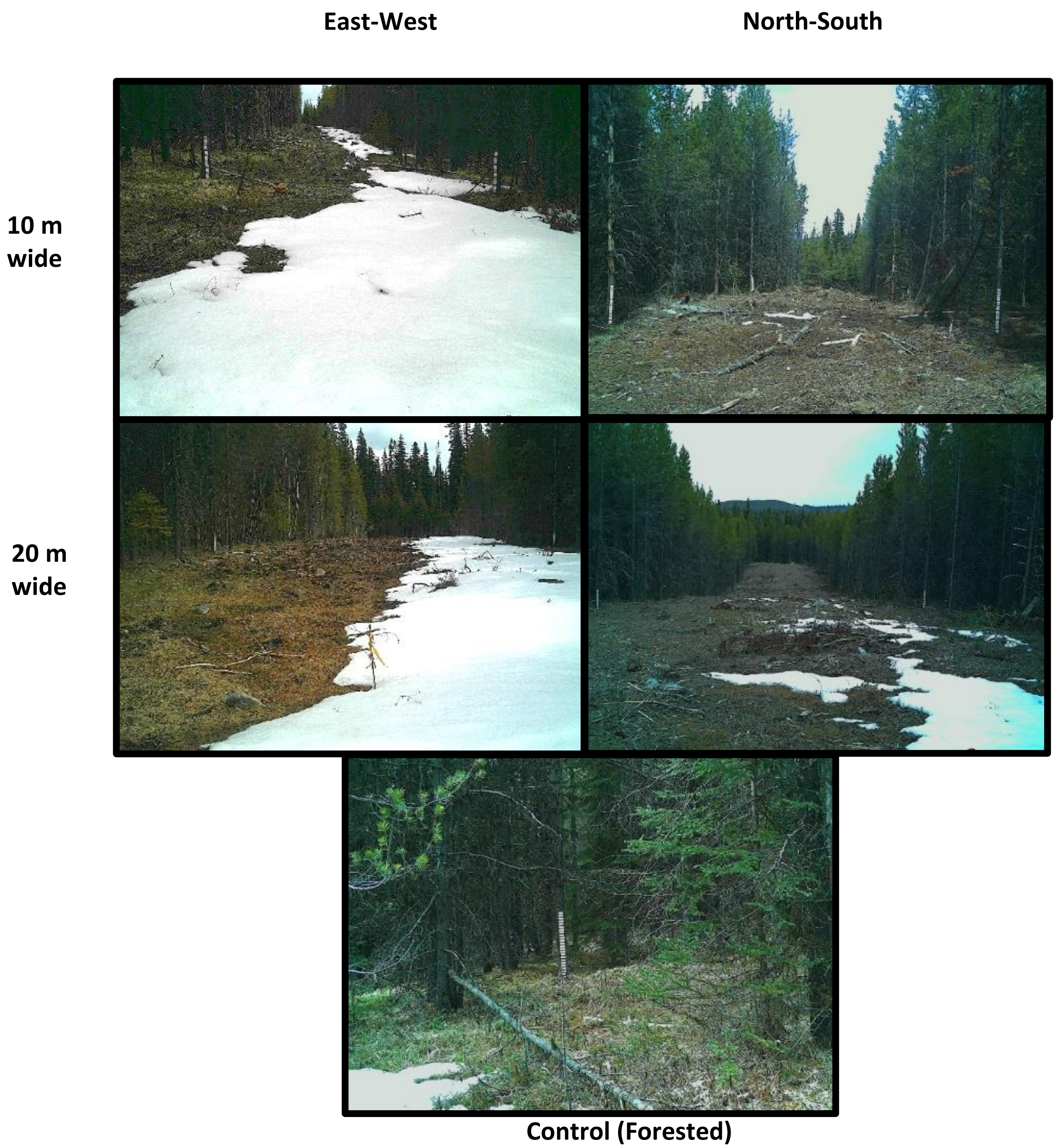

Figure C. 3. *Photos of snow pack observed simultaneously on May 1, 2019 at 12:00pm on permanently installed trail cameras. Delayed snow disappearance in east-west orientated strips, compared to north-south orientated strips. Snow has disappeared in forested areas and leave-strips.*

Figure C. 4. *Photo of east-west orientated (Block B) 10 m harvested trips, 20 m leave-strips, road, and clearcut with flat slope. Delayed snow disappearance was observed in 10m-wide harvested strips, relative to the road, clearcut, and forested stands. Photo taken: March 25, 2019.*

8.0 APPENDIX D

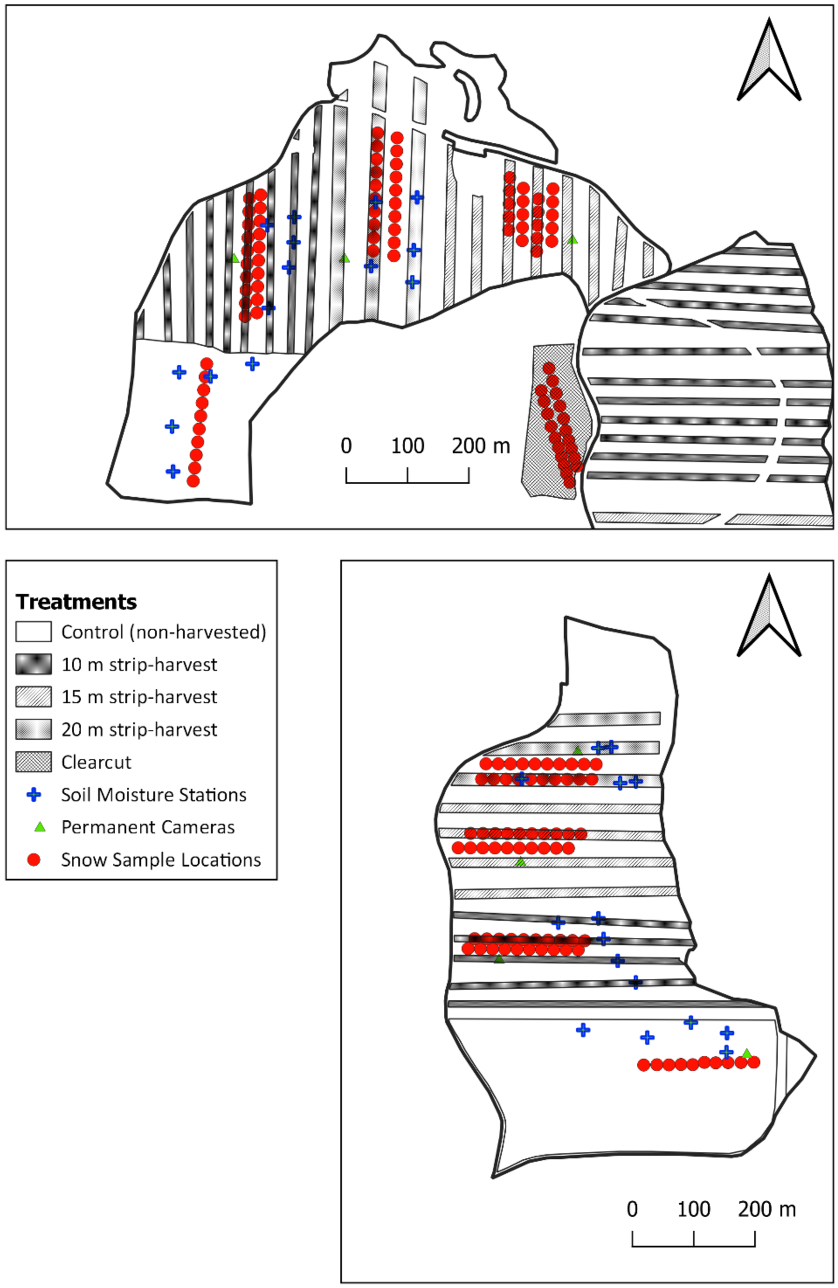

Figure D. 1*. Locations of all treatments, soil moisture stations, snow transects, and permanent cameras. Reserve strips are twice the width of adjacent harvested strips. Snow samples were at 20 m intervals along 180 m transects parallel to strip direction. All samples were located in the center of the strips (harvest or reserve).*

9.0 APPENDIX E

Table E. 1. *Summary of coarse fragment content (CFC) for each treatment. CFC was calculated as the percent volume of dried coarse material (sieved >2 mm, and assumed volume corrected assuming density of 2.65 Mg/m^3) of the total volume of the dried mineral sample. Summary includes standard deviation (SD), standard error (SE), 95 % confidence interval, and sample size (n).*

Harvested Strip-width	Orientation	Mean CFC (%)	SD	SE	95 % CI	n
10 m	North-south	16.2	3.7	0.91	1.95	16
10 m	East-west	19.2	7.8	1.95	4.15	16
15 m	North-south	19.8	11.7	2.92	6.23	16
15 m	East-west	17.1	10.0	2.50	5.33	16
20 m	North-south	17.4	5.5	1.36	2.91	16
20 m	East-west	25.5	16.8	4.20	8.95	16
Non-Harvested	North-south	12.7	3.2	0.81	1.72	16
Non-Harvested	East-west	10.6	7.4	1.84	3.93	16

Table E. 2. *Summary of dead forest floor litter depth by treatment. Summary includes standard deviation (SD), standard error (SE), 95 % confidence interval (CI), and sample size (n).*

Harvested Strip-width	Orientation	Mean Litter Depth (cm)	SD	SE	95 % CI	n
10 m	North-south	0.64	0.42	0.11	0.23	16
10 m	East-west	1.26	1.40	0.35	0.74	16
15 m	North-south	0.89	0.48	0.12	0.26	16
15 m	East-west	0.82	0.65	0.16	0.34	16
20 m	North-south	1.59	1.54	0.38	0.82	16
20 m	East-west	1.41	2.05	0.51	1.09	16
Non-Harvested	North-south	2.20	0.87	0.22	0.46	16
Non-Harvested	East-west	1.96	1.01	0.25	0.54	16

Table E. 3. *Summary of dead forest floor litter volume by treatment. Summary includes standard deviation (SD), standard error (SE), 95 % confidence interval (CI), and sample size (n).*

Harvested Strip-width	Orientation	Mean Litter Volume (mL)	SD	SE	95 % CI	n
10 m	North-south	256.50	170.60	42.65	90.90	16
10 m	East-west	502.50	559.23	139.81	297.99	16
15 m	North-south	355.69	192.71	48.18	102.69	16
15 m	East-west	327.50	258.50	64.62	137.74	16
20 m	North-south	635.00	614.82	153.70	327.61	16
20 m	East-west	560.56	818.29	204.57	436.04	16
Non-Harvested	North-south	880.00	347.79	86.95	185.33	16
Non-Harvested	East-west	785.00	404.47	101.12	215.53	16

Table E. 4. *Summary of dead forest floor litter mass by treatment. Summary includes standard deviation (SD), standard error (SE), 95 % confidence interval (CI), and sample size (n).*

Harvested Strip-width	Orientation	Mean Litter Mass (g)	SD	SE	95 % CI	n
10 m	North-south	31.75	25.24	6.31	13.45	16
10 m	East-west	57.23	46.60	11.65	24.83	16
15 m	North-south	56.03	34.13	8.53	18.19	16
15 m	East-west	41.36	21.31	5.33	11.36	16
20 m	North-south	67.42	48.85	12.21	26.03	16
20 m	East-west	54.98	90.43	22.61	48.19	16
Non-Harvested	North-south	47.08	19.83	4.96	10.57	16
Non-Harvested	East-west	47.79	21.99	5.50	11.72	16

Table E. 5. *Summary of the depth of dead forest floor fermented and humic organic soil layers (FH) by treatment. Summary includes standard deviation (SD), standard error (SE), 95 % confidence interval (CI), and sample size (n).*

Harvested Strip-width	Orientation	Mean FH Depth (cm)	SD	SE	95 % CI	n
10 m	North-south	3.11	2.45	0.61	1.31	16
10 m	East-west	4.96	2.64	0.66	1.40	16
15 m	North-south	4.81	2.19	0.55	1.17	16
15 m	East-west	4.55	3.54	0.88	1.89	16
20 m	North-south	4.27	2.78	0.70	1.48	16
20 m	East-west	6.54	3.71	0.93	1.97	16
Non-Harvested	North-south	4.63	3.32	0.83	1.77	16
Non-Harvested	East-west	3.88	2.44	0.61	1.30	16

Table E. 6. *Summary of the volume of dead forest floor fermented and humic organic soil layers (FH) by treatment. Summary includes standard deviation (SD), standard error (SE), 95 % confidence interval (CI), and sample size (n).*

Harvested Strip-width	Orientation	Mean FH Volume (mL)	SD	SE	95 % CI	n
10 m	North-south	1238.75	981.25	245.31	522.87	16
10 m	East-west	1985.00	1054.65	263.66	561.99	16
15 m	North-south	1915.63	871.73	217.93	464.51	16
15 m	East-west	1820.00	1415.27	353.82	754.14	16
20 m	North-south	1703.75	1112.94	278.23	593.04	16
20 m	East-west	2612.50	1479.58	369.90	788.41	16
Non-Harvested	North-south	1850.00	1326.69	331.67	706.94	16
Non-Harvested	East-west	1552.50	977.31	244.33	520.77	16

Table E. 7. *Summary of the mass of dead forest floor fermented and humic organic soil layers (FH) by treatment. Summary includes standard deviation (SD), standard error (SE), 95 % confidence interval (CI), and sample size (n).*

Harvested Strip-width	**Orientation**	**Mean FH Mass (g)**	**SD**	**SE**	**95 % CI**	**n**
10 m	North-south	292.64	272.72	68.18	145.32	16
10 m	East-west	500.69	302.69	75.67	161.29	16
15 m	North-south	493.11	338.23	84.56	180.23	16
15 m	East-west	477.42	550.17	137.54	293.17	16
20 m	North-south	470.78	477.90	119.47	254.65	16
20 m	East-west	808.05	669.59	167.40	356.80	16
Non-Harvested	North-south	269.25	228.78	57.20	121.91	16
Non-Harvested	East-west	304.38	345.95	86.49	184.34	16

10.0 APPENDIX F

Table F. 1. *Summary of snow sampling point terrain, maximum snow water equivalent (Max. SWE), and mean date of disappearance for 2019 and 2020, by transect (n=10). Snow was sampled between March 3 – May 8. Reserve strips were twice as wide as harvested strips. The strips were orientated North-South (N-S) or East-West (E-W). Means include 95% confidence interval.*

						2019		2020	
Tran-sect #	**Treatment**	**Strip Width (m)**	**Strip Orient-ation**	**Mean Aspect (°)**	**Mean Slope (°)**	**Mean Max. SWE (cm)**	**Mean date of disappearance**	**Mean Max. SWE (cm)**	**Mean date of disappearance**
1	Harvested Strip	10	N-S	312 ± 1.8	6 ± 0	16.3 ± 1.7	Apr-30 ± 3.0	28.7 ± 1.2	May-14 ± 2.2
2	Harvested Strip	15	N-S	21 ± 0.9	3 ± 0	16.8 ± 0.9	Apr-29 ± 2.5	29.9 ± 1.2	May-14 ± 1.1
3	Harvested Strip	20	N-S	199 ± 2.0	7.3 ± 0.1	18.8 ± 2.3	Apr-30 ± 3.0	31.1 ± 1.6	May-14 ± 1.6
4	Harvested Strip	10	E-W	216 ± 1.1	10 ± 0	16.8 ± 0.9	May-01 ± 2.8	28.5 ± 1.1	May-11 ± 4.0
5	Harvested Strip	15	E-W	236 ± 1.3	8 ± 0	18.6 ± 1.6	May-01 ± 2.6	29.4 ± 1.2	May-11 ± 3.7
6	Harvested Strip	20	E-W	248 ± 4.0	7 ± 0	21.3 ± 1.3	Apr-29 ± 2.8	30.1 ± 1.7	May-05 ± 3.0
7	Reserve Strip	20	N-S	313 ± 2.0	6 ± 0	9.9 ± 1.7	Apr-18 ± 5.2	18.6 ± 3	May-05 ± 2.7
8	Reserve Strip	30	N-S	76 ± 2.6	2.6 ± 0.2	10.1 ± 2.0	Apr-21 ± 4.1	18.7 ± 2.5	May-10 ± 3.3
9	Reserve Strip	40	N-S	72 ± 2.6	6.6 ± 0.1	11.5 ± 2	Apr-24 ± 5.0	20.3 ± 2.2	May-10 ± 3.8
10	Reserve Strip	20	E-W	217 ± 1.3	10 ± 0	9.1 ± 1.2	Apr-06 ± 9.4	17.8 ± 2	May-03 ± 1.0
11	Reserve Strip	30	E-W	229 ± 1.7	8 ± 0	12.4 ± 2.7	Apr-15 ± 2.8	17.8 ± 1.6	May-05 ± 3.1
12	Reserve Strip	40	E-W	307 ± 1.4	7 ± 0	11.3 ± 1.0	Apr-11 ± 5.7	16.9 ± 1.4	May-03 ± 1.0
13	Non-harvested	-	-	283 ± 2.6	6 ± 0	7.4 ± 1.1	Apri-22 ± 4.8	18.5 ± 3.3	May-09 ± 3.4
14	Non-harvested	-	-	199 ± 4.1	2 ± 0	10.9 ± 2.3	Apr-23 ± 6.1	21.9 ± 3.9	May-14 ± 2.6
15	Clearcut	-	-	116 ± 0.0	1.6 ± 0.3	17.1 ± 1.6	Apr-23 ± 5	28 ± 2.5	May-05 ± 2.1
16	Clearcut	-	-	116 ± 0.0	1 ± 0	-	-	28.7 ± 1.7	May-04 ± 1.5

Table F. 2. *Snow ablation rates for 2019, summarized by transect (n=10). Snow was sampled between March 3 – May 5. Ablation was calculated by the difference in snow water equivalent (SWE) from the previous sample period divided by the number of days between sampling (cm/day). Average ablation rate was taken as an average of all of the mean rates by sampling period. Reserve strips were twice as wide as harvested strips. The strips were orientated North-South (N-S) or East-West (E-W). Means include 95% confidence interval.*

Transect #	Treatment	Strip Width (m)	Strip Orientation	Ablation Rate (cm/day) 2019-Mar-29	Ablation Rate (cm/day) 2019-Apr-12	Ablation Rate (cm/day) 2019-Apr-26	Ablation Rate (cm/day) 2019-May-5	Ablation Rate (cm/day) 2019 Average
1	Harvested Strip	10	N-S	-0.05 ± 0.14	-0.23 ± 0.09	-0.6 ± 0.14	-0.3 ± 0.24	-0.43 ± 0.05
2	Harvested Strip	20	N-S	-0.24 ± 0.09	-0.09 ± 0.1	-0.63 ± 0.11	-0.46 ± 0.37	-0.39 ± 0.04
3	Harvested Strip	15	N-S	-0.14 ± 0.05	-0.13 ± 0.1	-0.69 ± 0.09	-0.26 ± 0.21	-0.45 ± 0.09
4	Harvested Strip	10	E-W	-0.23 ± 0.09	-0.24 ± 0.11	-0.73 ± 0.12	-0.33 ± 0.3	-0.47 ± 0.06
5	Harvested Strip	15	E-W	-0.02 ± 0.13	-0.11 ± 0.16	-0.74 ± 0.18	-0.6 ± 0.29	-0.53 ± 0.06
6	Harvested Strip	20	E-W	0.22 ± 0.18	-0.19 ± 0.06	-0.65 ± 0.05	-0.53 ± 0.29	-0.46 ± 0.06
7	Reserve Strip	10	N-S	-0.26 ± 0.12	-0.19 ± 0.09	-0.09 ± 0.1	-0.04 ± 0.1	-0.25 ± 0.06
8	Reserve Strip	40	N-S	-0.23 ± 0.1	-0.22 ± 0.19	-0.25 ± 0.12	-	-0.32 ± 0.2
9	Reserve Strip	30	N-S	-0.06 ± 0.16	-0.34 ± 0.25	-0.18 ± 0.08	-	-0.29 ± 0.05
10	Reserve Strip	40	E-W	-0.44 ± 0.06	-0.15 ± 0.09	-0.03 ± 0.06	-	-0.36 ± 0.08
11	Reserve Strip	30	E-W	-0.22 ± 0.21	-0.42 ± 0.3	-0.06 ± 0.05	-	-0.4 ± 0.3
12	Reserve Strip	20	E-W	-0.36 ± 0.08	-0.06 ± 0.08	-0.07 ± 0.08	-	-0.36 ± 0.05
13	Non-harvested	-	-	-0.16 ± 0.08	-0.16 ± 0.07	-0.13 ± 0.07	-	-0.18 ± 0.03
14	Non-harvested	-	-	-0.22 ± 0.22	-0.1 ± 0.33	-0.23 ± 0.14	-0.1 ± 0.12	-0.39 ± 0.11
15	Clearcut	-	-	-0.29 ± 0.07	-0.39 ± 0.25	-0.39 ± 0.16	-	-0.43 ± 0.06

Table F. 3. *Snow ablation rates for 2020, summarized by transect (n=10). Snow was sampled between March 7 – May 8. Ablation was calculated by the difference in snow water equivalent (SWE) from the previous sample period divided by the number of days between sampling (cm/day). Average ablation rate was taken as an average of all of the mean rates by sampling period. Reserve strips were twice as wide as harvested open-strips. Strips were orientated North-South (N-S) or East-West (E-W). Means include 95% confidence interval.*

Transect #	Treatment	Strip Width (m)	Strip Orient-ation	Ablation Rate (cm/day) 2020-Mar-27	Ablation Rate (cm/day) 2020-Apr-10	Ablation Rate (cm/day) 2020-Apr-24	Ablation Rate (cm/day) 2020-May-2	Ablation Rate (cm/day) 2020-May 8	Ablation Rate (cm/day) 2020 Average
1	Harvested Strip	10	N-S	0.11 ± 0.08	-0.14 ± 0.11	-0.43 ± 0.13	-1.26 ± 0.12	-0.48 ± 0.19	-0.63 ± 0.11
2	Harvested Strip	20	N-S	0.15 ± 0.11	-0.07 ± 0.18	-0.5 ± 0.14	-1.23 ± 0.12	-0.57 ± 0.3	-0.7 ± 0.09
3	Harvested Strip	15	N-S	0.1 ± 0.09	-0.15 ± 0.27	-0.31 ± 0.17	-1.26 ± 0.2	-0.62 ± 0.23	-0.67 ± 0.07
4	Harvested Strip	20	E-W	0.11 ± 0.11	-0.05 ± 0.14	-0.73 ± 0.23	-1.94 ± 0.39	-0.42 ± 0.37	-0.81 ± 0.17
5	Harvested Strip	15	E-W	0.05 ± 0.07	-0.06 ± 0.12	-0.52 ± 0.12	-1.6 ± 0.29	-0.53 ± 0.34	-0.85 ± 0.15
6	Harvested Strip	10	E-W	0.03 ± 0.09	-0.05 ± 0.13	-0.49 ± 0.14	-1.57 ± 0.29	-0.47 ± 0.38	-1.07 ± 0.23
7	Reserve Strip	10	N-S	0.04 ± 0.08	-0.13 ± 0.15	-0.44 ± 0.1	-0.88 ± 0.18	-0.32 ± 0.29	-0.5 ± 0.07
8	Reserve Strip	40	N-S	0.09 ± 0.24	-0.05 ± 0.39	-0.36 ± 0.41	-0.86 ± 0.18	-0.4 ± 0.2	-0.53 ± 0.06
9	Reserve Strip	30	N-S	0.1 ± 0.08	-0.2 ± 0.13	-0.3 ± 0.14	-0.89 ± 0.18	-0.4 ± 0.24	-0.62 ± 0.09
10	Reserve Strip	40	E-W	0.12 ± 0.12	-0.29 ± 0.16	-0.34 ± 0.11	-0.9 ± 0.17	-0.1 ± 0.12	-0.5 ± 0.1
11	Reserve Strip	30	E-W	0.03 ± 0.13	-0.06 ± 0.22	-0.44 ± 0.15	-1 ± 0.18	-0.2 ± 0.15	-0.62 ± 0.13
12	Reserve Strip	20	E-W	0.07 ± 0.08	-0.31 ± 0.12	-0.54 ± 0.08	-0.68 ± 0.22	-0.1 ± 0.16	-0.5 ± 0.06
13	Non-harvested	-	-	0.05 ± 0.13	-0.03 ± 0.3	-0.39 ± 0.25	-0.8 ± 0.16	-0.17 ± 0.28	-0.44 ± 0.07
14	Non-harvested	-	-	-0.02 ± 0.21	0.05 ± 0.23	-0.33 ± 0.13	-0.86 ± 0.21	-0.23 ± 0.36	-0.48 ± 0.07
15	Clearcut	-	-	0.09 ± 0.08	-0.04 ± 0.21	-0.61 ± 0.15	-1.69 ± 0.41	-0.67 ± 0.37	-0.89 ± 0.11
16	Clearcut	-	-	0.11 ± 0.09	-0.09 ± 0.17	-0.51 ± 0.18	-2.11 ± 0.35	-0.48 ± 0.32	-1.07 ± 0.18

Table F. 4. *Summary of means and 95 % confidence intervals for terrain, canopy cover, estimated transmitted direct radiation, peak snow water equivalent (SWE), date of snow disappearance, and average ablation rate for harvested strips of various widths (10-20 m) and of two orientations (North-South and East-West). Non-harvested and clearcut controls were also included. Snow was sampled between March 3 – May 5, 2019 and 2020.*

	North-South			**East-West**			**Control Non-Harvested**	**Control Clearcut**
	10 m	**15 m**	**20 m**	**10 m**	**15 m**	**20 m**		
Elevation (m)	1382.8 ± 0.7	1383.6 ± 0.3	1385.9 ± 0.7	1357.2 ± 0.7	1367.6 ± 0.9	1372.8 ± 0.8	1373 ± 1.8	1389.2 ± 0.1
Slope (°)	6 ± 0	3 ± 0	7.3 ± 0.1	10 ± 0	8 ± 0	7 ± 0	4 ± 0.3	1.4 ± 0.2
Aspect (°)	312 ± 1.8	21 ± 0.9	199 ± 2.0	216 ± 1.1	236 ± 1.3	248 ± 4.0	240 ± 5.9	116 ± 0.0
Canopy cover (%)	61.9 ± 0.6	47.5 ± 0.3	42.6 ± 0.3	59.4 ± 0.4	50.6 ± 0.3	41.2 ± 0.2	86.1 ± 0.5	13.2 ± 0.2
Trans. Direct Rad. (MJ/m2/d)	3.7 ± 0.1	5.3 ± 0.1	5.1 ± 0.1	2.5 ± 0.1	3.1 ± 0.1	4.7 ± 0.1	1.2 ± 0.1	9.3 ± 0.1
2019 - Peak SWE (cm)	16.3 ± 1.7	16.8 ± 0.9	18.8 ± 2.3	16.8 ± 0.9	18.6 ± 1.6	21.3 ± 1.3	9.2 ± 1.4	17.1 ± 1.6
2019 – Date of Disappearance	Apr-30 ± 3	Apr-29 ± 2.5	Apr-30 ± 3	May-01 ± 2.8	May-01 ± 2.6	Apr-29 ± 2.8	Apr-22 ± 3.5	Apr-23 ± 4.9
2019 – Avg. Ablation rate (cm/day)	-0.43 ± 0.05	-0.39 ± 0.04	-0.45 ± 0.09	-0.47 ± 0.06	-0.53 ± 0.06	-0.46 ± 0.06	-0.28 ± 0.07	-0.43 ± 0.06
2020 - Peak SWE 2020 (cm)	28.7 ± 1.2	29.9 ± 1.2	31.1 ± 1.6	28.5 ± 1.1	29.4 ± 1.2	30.1 ± 1.7	20.2 ± 2.4	28.4 ± 1.4
2020 – Date of Disappearance	May-14 ± 2.2	May-15 ± 0.7	May-14 ± 1.6	May-11 ± 4	May-11 ± 3.7	May-05 ± 3	May-11 ± 2.2	May-05 ± 1.2
2020 – Avg. Ablation rate (cm/day)	-0.63 ± 0.11	-0.7 ± 0.09	-0.67 ± 0.07	-0.81 ± 0.17	-0.85 ± 0.15	-1.07 ± 0.23	-0.46 ± 0.05	-0.98 ± 0.1

Table F. 5. *Summary of means and 95 % confidence intervals for terrain, canopy cover, estimated transmitted direct radiation, peak snow water equivalent (SWE), date of snow disappearance, and average ablation rate for reserve strips of various widths (10-20 m) and of two orientations (North-South and East-West). Reserve strips were twice the width of adjacent harvested strips. Non-harvested and clearcut controls were also included. Snow was sampled between March 3 – May 5, 2019 and 2020.*

	North-South			East-West			Control Non-Harvested	Control Clearcut
	20 m	**30 m**	**40 m**	**20 m**	**30 m**	**40 m**		
Elevation (m)	1384.1 ± 0.9	1383.3 ± 0.2	1386.9 ± 0.7	1355.5 ± 0.7	1364.9 ± 0.9	1373.6 ± 0.7	1373 ± 1.8	1389.2 ± 0.1
Slope (°)	6 ± 0	2.6 ± 0.1	6.3 ± 0.2	10 ± 0	8 ± 0	7 ± 0	4 ± 0.3	1.4 ± 0.2
Aspect (°)	313 ± 2.0	76 ± 2.6	72 ± 2.6	217 ± 1.3	229 ± 1.7	307 ± 1.4	240 ± 5.9	116 ± 0.0
Canopy cover (%)	85 ± 0.5	76.8 ± 0.5	77.2 ± 0.3	81.2 ± 0.4	84.2 ± 0.3	78.1 ± 0.4	86.1 ± 0.5	13.2 ± 0.2
Trans. Direct Rad. (MJ/m2/d)	1.0 ± 0.1	1.5 ± 0.1	1.4 ± 0.1	2.6 ± 0.2	2.2 ± 0.1	2.4 ± 0.1	1.2 ± 0.1	9.3 ± 0.1
2019 - Peak SWE (cm)	9.9 ± 1.7	10.1 ± 2	11.5 ± 2	9.1 ± 1.2	12.4 ± 2.7	11.3 ± 1	9.2 ± 1.4	17.1 ± 1.6
2019 – Date of Disappearance	Apr-18 ± 5.2	Apr-21 ± 4.1	Apr-24 ± 5	Apr-06 ± 9.3	Apr-15 ± 2.8	Apr-11 ± 5.7	Apr-22 ± 3.5	Apr-23 ± 4.9
2019 – Avg. Ablation rate (cm/day)	-0.25 ± 0.06	-0.32 ± 0.2	-0.29 ± 0.05	-0.36 ± 0.08	-0.4 ± 0.3	-0.36 ± 0.05	-0.28 ± 0.07	-0.43 ± 0.06
2020 - Peak SWE 2020 (cm)	18.6 ± 3	18.7 ± 2.5	20.3 ± 2.2	17.8 ± 2	17.8 ± 1.6	16.9 ± 1.4	20.2 ± 2.4	28.4 ± 1.4
2020 – Date of Disappearance	May-05 ± 2.7	May-09 ± 3.4	May-10 ± 3.3	May-03 ± 1	May-05 ± 3.1	May-03 ± 1	May-11 ± 2.2	May-05 ± 1.2
2020 – Avg. Ablation rate (cm/day)	-0.5 ± 0.07	-0.53 ± 0.06	-0.62 ± 0.09	-0.5 ± 0.1	-0.62 ± 0.13	-0.5 ± 0.06	-0.46 ± 0.05	-0.98 ± 0.1

***Table F. 6**. Results of a Tukey post-hoc test, summarizing the mean number of days between snow disappearance observed in all treatments in 2019.*

Treatment #1	Treatment #2	Mean Number of Days Treatment #1 Disappeared Before Treatment #2	95 % CI	P-Value
20m - Reserve	20m - Harvest	17.7	± 7.1	<0.0001
20m - Reserve	15m - Harvest	18.2	± 7.1	<0.0001
20m - Reserve	10m - Harvest	18.4	± 7.1	<0.0001
40m - Reserve	20m - Harvest	12.4	± 7.1	<0.0001
40m - Reserve	15m - Harvest	12.9	± 7.1	<0.0001
40m - Reserve	10m - Harvest	13.2	± 7.1	<0.0001
30m - Reserve	20m - Harvest	11.8	± 7.1	<0.0001
30m - Reserve	15m - Harvest	12.3	± 7.1	<0.0001
30m - Reserve	10m - Harvest	12.6	± 7.1	<0.0001
20m - Reserve	No - Harvest	10.1	± 7.1	0.0006
20m - Reserve	Clearcut	11.4	± 8.7	0.0023
No - Harvest	20m - Harvest	7.6	± 7.1	0.0289
No - Harvest	15m - Harvest	8.0	± 7.1	0.0148
No - Harvest	10m - Harvest	8.3	± 7.1	0.0104
20m - Reserve	40m - Reserve	5.2	± 7.1	0.3167
20m - Reserve	30m - Reserve	5.8	± 7.1	0.1911
40m - Reserve	30m - Reserve	0.6	± 7.1	1.0000
40m - Reserve	No - Harvest	4.9	± 7.1	0.4210
40m - Reserve	Clearcut	6.2	± 8.7	0.3746
30m - Reserve	No - Harvest	4.3	± 7.1	0.5949
30m - Reserve	Clearcut	5.6	± 8.7	0.5121
No - Harvest	Clearcut	1.3	± 8.7	0.9998
Clearcut	20m - Harvest	6.3	± 8.7	0.3534
Clearcut	15m - Harvest	6.8	± 8.7	0.2570
Clearcut	10m - Harvest	7.0	± 8.7	0.2157
20m - Harvest	15m - Harvest	0.5	± 7.1	1.0000
20m - Harvest	10m - Harvest	0.8	± 7.1	1.0000
15m - Harvest	10m - Harvest	0.3	± 7.1	1.0000

Table F. 7. *Results of a Tukey post-hoc test, summarizing the mean number of days between snow disappearance observed in all treatments in 2020.*

Treatment #1	Treatment #2	Mean Number of Days Treatment #1 Disappeared Before Treatment #2	95 % CI	P-Value
30m - Reserve	20m - Harvest	2.3	± 4.4	<0.0001
40m - Reserve	15m - Harvest	6.2	± 4.3	<0.0001
30m - Reserve	No - Harvest	4.1	± 4.4	<0.0001
40m - Reserve	No - Harvest	4.9	± 4.3	<0.0001
30m - Reserve	15m - Harvest	5.4	± 4.4	<0.0001
40m - Reserve	10m - Harvest	5.8	± 4.3	<0.0001
20m - Reserve	40m - Reserve	2.8	± 4.3	0.0005
Clearcut	15m - Harvest	8.2	± 4.4	0.0014
Clearcut	20m - Harvest	5.1	± 4.4	0.0016
Clearcut	30m - Reserve	2.8	± 4.4	0.0056
No - Harvest	10m - Harvest	0.9	± 4.4	0.0102
No - Harvest	15m - Harvest	1.3	± 4.4	0.0144
40m - Reserve	30m - Reserve	0.8	± 4.3	0.0148
20m - Reserve	10m - Harvest	8.5	± 4.4	0.0897
20m - Reserve	No - Harvest	7.7	± 4.4	0.1882
Clearcut	No - Harvest	6.8	± 4.4	0.3392
Clearcut	40m - Reserve	2.0	± 4.3	0.3886
10m - Harvest	15m - Harvest	0.4	± 4.4	0.5011
20m - Harvest	No - Harvest	1.7	± 4.4	0.5035
20m - Reserve	Clearcut	0.8	± 4.4	0.5754
20m - Harvest	15m - Harvest	3.1	± 4.4	0.7372
40m - Reserve	20m - Harvest	3.1	± 4.3	0.9208
20m - Reserve	20m - Harvest	5.9	± 4.4	0.9841
20m - Reserve	15m - Harvest	9.0	± 4.4	0.9983
30m - Reserve	10m - Harvest	4.9	± 4.4	0.9989
Clearcut	10m - Harvest	7.7	± 4.4	0.9992
20m - Reserve	30m - Reserve	3.6	± 4.4	1.0000

Table F. 8. *Results of a Tukey post-hoc test, summarizing the mean number of days between snow disappearance observed in* *2019* *between all reserve-strips orientated east-west (E-W), all reserve-strips orientated east-west (N-S), all strip-harvests orientated north-south (N-S), all strip-harvests orientated east-west (E-W), as well as clearcut and non-harvested controls.*

Treatment #1	Treatment #2	Mean Number of Days Treatment #1 Disappeared Before Treatment #2	95 % CI	P-Value
Reserve-strips E-W	Strip-Harvests N-S	18.9	5.0	< 0.0001
Reserve-strips E-W	Strip-Harvests E-W	20.0	5.0	< 0.0001
Reserve-strips E-W	Non-Harvested	11.5	5.6	< 0.0001
Reserve-strips E-W	Reserve-strips N-S	10.2	5.0	< 0.0001
Reserve-strips N-S	Strip-Harvests E-W	9.8	5.0	< 0.0001
Reserve-strips E-W	Clearcut	12.8	7.0	< 0.0001
Reserve-strips N-S	Strip-Harvests N-S	8.7	5.0	< 0.0001
Non-Harvested	Strip-Harvests E-W	8.5	5.6	0.0003
Non-Harvested	Strip-Harvests N-S	7.4	5.6	0.0024
Clearcut	Strip-Harvests E-W	7.2	7.0	0.0421
Clearcut	Strip-Harvests N-S	6.1	7.0	0.1269
Reserve-strips N-S	Clearcut	2.6	7.0	0.8941
Reserve-strips N-S	Non-Harvested	1.3	5.6	0.9845
Strip-Harvests N-S	Strip-Harvests E-W	1.1	5.0	0.9895
Non-Harvested	Clearcut	1.3	7.5	0.9960

Table F. 9. *Results of a Tukey post-hoc test, summarizing the mean number of days between snow disappearance observed in 2020 between all reserve-strips orientated east-west (E-W), all reserve-strips orientated east-west (N-S), all strip-harvests orientated north-south (N-S), all strip-harvests orientated east-west (E-W), as well as clearcut and non-harvested controls.*

Treatment #1	Treatment #2	Mean Number of Days Treatment #1 Disappeared Before Treatment #2	95 % CI	P-Value
Reserve-strips E-W	Strip-Harvests N-S	10.7	3.0	< 0.0001
Clearcut	Strip-Harvests N-S	9.7	3.4	< 0.0001
Reserve-strips E-W	Non-Harvested	7.9	3.4	< 0.0001
Reserve-strips N-S	Strip-Harvests N-S	6.0	3.0	< 0.0001
Clearcut	Non-Harvested	6.9	3.7	< 0.0001
Reserve-strips E-W	Strip-Harvests E-W	5.4	3.0	< 0.0001
Strip-Harvests E-W	Strip-Harvests N-S	5.3	3.0	< 0.0001
Reserve-strips E-W	Reserve-strips N-S	4.7	3.0	0.0002
Clearcut	Strip-Harvests E-W	4.3	3.4	0.0042
Clearcut	Reserve-strips N-S	3.6	3.4	0.0273
Reserve-strips N-S	Non-Harvested	3.2	3.4	0.0701
Non-Harvested	Strip-Harvests N-S	2.8	3.4	0.1650
Strip-Harvests E-W	Non-Harvested	2.5	3.4	0.2733
Reserve-strips E-W	Clearcut	1.0	3.4	0.9513
Reserve-strips N-S	Strip-Harvests E-W	0.7	3.0	0.9842

Table F. 10. *Results of a Games-Howell pairwise comparison test used to determine effects of treatments on estimated transmitted direct radiation (MJ/m^2/d) in harvested strips of commercially thinned stands of various widths (10, 15, 20m). Strip-width of harvested strips and strip-orientation were fixed independent variables. NS = north-south, EW = east-west*

Group 1	Group 2	Estimated difference in transmitted direct radiation (MJ/m^2/d)	95 % CI	P-Value
Clearcut	NS.10m	-5.64	±0.77	< 0.001
Clearcut	NS.15m	-3.99	±0.47	<0.001
Clearcut	NS.20m	-4.20	±0.28	< 0.001
Clearcut	NS.No-Harvest	-8.34	±0.65	< 0.001
Clearcut	EW.10m	-6.75	±0.98	< 0.001
Clearcut	EW.15m	-6.19	±0.44	< 0.001
Clearcut	EW.20m	-4.20	±1.79	< 0.001
Clearcut	EW.No-Harvest	-7.88	±0.36	< 0.001
NS.10m	NS.15m	1.64	±0.81	< 0.001
NS.10m	NS.20m	1.43	±0.77	< 0.001
NS.10m	NS.No-Harvest	-2.70	±0.89	< 0.001
NS.10m	EW.10m	-1.11	±1.1	0.047
NS.10m	EW.15m	-0.55	±0.8	0.31
NS10m	EW.20m	1.43	±1.82	0.18
NS10m	EW.No-Harvest	-2.23	±0.79	< 0.001
NS15m	NS.20m	-0.20	±0.49	0.8
NS15m	NS.No-Harvest	-4.34	±0.72	< 0.001
NS15m	EW.10m	-2.76	±1	< 0.001
NS15m	EW.15m	-2.20	±0.56	< 0.001
NS15m	EW.20m	-0.21	±1.793	1
NS15m	EW.No-Harvest	-3.88	±0.52	< 0.001
NS20m	NS.No-Harvest	-4.13	±0.66	< 0.001
NS20m	EW.10m	-2.55	±0.97	< 0.001
NS20m	EW.15m	-1.99	±0.45	< 0.001
NS20m	EW.20m	-0.001	±1.779	1
NS20m	EW.No-Harvest	-3.67	±0.38	< 0.001
NS.No-Harvest	EW.10m	1.58	±1.05	0.002
NS.No-Harvest	EW.15m	2.14	±0.7	< 0.001
NS.No-Harvest	EW.20m	4.13	±1.81	< 0.001
NS.No-Harvest	EW.No-Harvest	0.46	±0.67	0.31
EW.10m	EW.15m	0.55	±0.98	0.528
EW.10m	EW.20m	2.54	±1.87	0.005
EW.10m	EW.No-Harvest	-1.12	±0.98	0.022
EW.15m	EW.20m	1.99	±1.79	0.026
EW.15m	EW.No-Harvest	-1.68	±0.5	< 0.001
EW.20m	EW.No-Harvest	-3.67	±1.78	< 0.001